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THE FINAL CONSOLIDATION PHENOMENA IN THE CRYSTALLIZATION OF IGNEOUS ROCK

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Pyrogenetic processes may, for convenience, be divided into (*a*) effects produced within the igneous rock mass itself, and (*b*) effects produced by the end-stage consolidation products (aqueo-igneous matters) upon the neighboring rocks into which these matters have been forced.

The effects produced within the igneous rock itself are due in part to molecular changes taking place in the various individual minerals which crystallize during consolidation, some of them possessing one or more different allotropic forms into which they pass as the temperature of the rock-mass falls through the various critical ranges where such inversions are effected; in part to actual reactions occurring between some of the component minerals of the rock already crystallized and the remaining still-molten magma;[1] and in part to reactions due to adjustments of equilibrium between the extreme end-stage, highly concentrated "mother-liquor" which, by selective freezing, has been enriched with the more volatile gases usually termed "mineralizers," among which water

[1] N. L. Bowen, "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

plays an important part, and the now almost wholly consolidated rock. These equilibrium adjustments, and the changes produced by chemical attack, may be thought of as an extension of the reaction effects described by Bowen. At this stage much of the quartz and some of the alkalies, especially soda in such form as to appear ultimately as albite, seem to be concentrated in the form of a liquid consolidation-residuum, which, from such evidence as is presented in the rocks themselves, must possess an extremely low viscosity, great penetrating power, and considerable chemical activity.

During the consolidation of plutonic rocks especially, the mineralizers operate to effect changes in some of the already formed minerals, and in some cases cause profound changes in the rock itself. When present to only a small extent their effects are usually confined to the parent igneous rock. This is exhibited in various ways. Frequently the end-phase products, quartz and albite, penetrate the earlier feldspars, converting earlier orthoclase into a sort of "injection perthite," beautifully exhibited in a granite near Fort Ann, New York, and illustrated by Figure 1. In this granite each feldspar grain is surrounded by a narrow rim or border of quartz and albite, which likewise penetrate the grains irregularly and form also veinlets of microscopic dimensions in the rock. Lying in and associated with such veinlets is a little graphite, which apparently is of the same origin as the end-stage material itself. The rock carries a little orthorhombic pyroxene as one of the ferromagnesian components and this, wherever it appears, has been converted to serpentine, which is here an end-stage reaction product originating partly because of changes in equilibrium, and partly because of hydration during the last stages of crystallization of the rock.

Sederholm[1] describes as "deuteric effects" certain products occurring as an intergrowth of two minerals at their contacts by reason of the action of magmatic end-stage emanations; but the structures thus described are very minute. The writer has extended the term to cover all magmatic end-stage emanation phenomena,

[1] J. J. Sederholm, "Synantetic Minerals and Related Phenomena," *Bull. de la Com. Geol. de Finlande*, No. 48.

which frequently cause large-scale changes and very profound effects, especially in the way of mineralization.

Another illustration of the same process is shown in Figures 2 and 3. In this case the rock, a diorite from Newfoundland, is self-injected in the same manner, but the effects are more profound. The original ferromagnesian mineral has been wholly converted to a

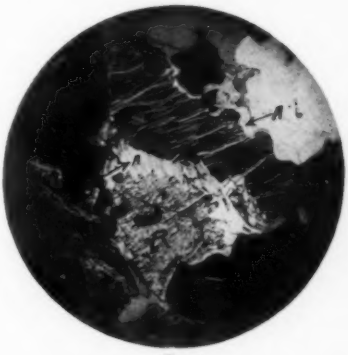

FIG. 1

FIG. 2

FIG. 1.—Photomicrograph of deuterized granite, Fort Ann, New York. Nicols crossed, magnification 20 diameters. The earlier feldspar is orthoclase, which has been heavily injected with end-stage consolidation products consisting of quartz and albite (*A*). These products are both interstitial, and injected through the rock, on a microscopic scale. The black grains are quartz at the position of extinction. A crystal of orthorhombic pyroxene (*P*) has been converted to serpentine by the same agents and during the last stages of crystallization.

FIG. 2.—Photomicrograph of diorite from Newfoundland. Nicols crossed, magnification 20 diameters. Coarsely granitoid in texture; the single large crystal (dark gray) is an earlier plagioclase feldspar of andesine composition thoroughly injected with end-stage quartz and albite. Connected with this stage and because of changes in equilibrium, together with hydration effects, the ferromagnesian mineral (*A*) has been converted to an interlacing mat of actinolite needles.

complex of matted actinolite needles and the plagioclase, otherwise quite fresh and unaltered, has been thoroughly injected and soaked with quartz and albite; changes obviously connected with end-stage emanation products of a dioritic magma.

Even in more basic rocks such phenomena are common where the mass is of sufficient extent to have permitted more or less crystallization-differentiation. In the diabase which forms the

palisades along the Hudson River in New Jersey and New York, the usually resistant aluminous augite has been affected by precisely similar processes, so that in places it is partly converted into a complex of green hornblende (almost actinolite), brown biotite and magnetite dust, frequently associated with end-stage quartz. A quartz-rich phase is found near the top of the same intruded sheet, quartz usually occurring in coarse micrographic intergrowths

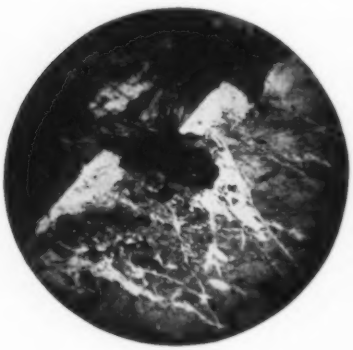

FIG. 3

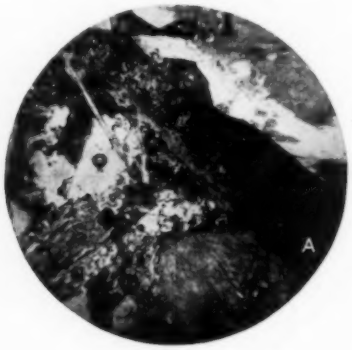

FIG. 4

FIG. 3.—Photomicrograph of diorite from Newfoundland. The same rock shown in Figure 2, but taken from another part of the thin section. Nicols crossed, magnification 20 diameters. The acicular aggregate is actinolite. Note the way in which the late-stage product (white) injects the plagioclase (gray).

FIG. 4.—Photomicrograph of Palisades diabase. Nicols crossed, magnification 20 diameters. An augite crystal (*A*) with pinacoidal parting indistinctly shown, has been partly converted to a complex of actinolite, magnetite, chlorite and biotite. Quartz (*Q*) of late-stage crystallization is in contact with the augite. Illustrative of equilibrium changes due to reaction effects between the quartz-alkali rich final consolidation product and earlier formed crystals.

with orthoclase. This is illustrated in Figure 4; an augite crystal (*A*), showing indistinctly pinacoidal parting, has been in part converted to a complex of actinolitic hornblende, biotite, magnetite, and chlorite; end-stage quartz (*Q*) is associated with these products, and it seems reasonable to conclude that the quartz-rich alkali-rich liquid residuum must have been responsible for the chemical changes involved, together with equilibrium changes occurring because of the different conditions of temperature and concentration.

Olivine and magnesia-rich pyroxenes are particularly susceptible to magmatic end-stage products. Peridotites, olivine-rich pyroxenites and dunites thus are converted to great masses of serpentine; not by "weathering," but during cooling and final consolidation.

This was recognized many years ago by De Launay[1] during his studies of ore deposits, and expressed as follows:

> Il resterait, d'alleurs, á examiner si cette serpentinisation même n'est pas souvent contemporaine de la cristallisation (comme paraitrait le prouver sa persistance à de très grandes profondeurs) et si elle n'a pas été produite par un excès de vapeur d'eau, dont la presence, dans le magma fondu, aurait pu, en même temps, faciliter la concentration metallique.

Where basic magmas are involved, crystallization-differentiation may concentrate sufficient quantities of the more acid end-stage products to cause profound changes to take place and to produce ore-bodies of magnitude and commercial importance. The nickeliferous "norites" of the Sudbury region in Ontario, and the Maskwa River norite in Manitoba are examples of such large-scale effects. The "norites" of these areas have been so extensively changed that in many instances they do not resemble true norites either mineralogically or chemically. Their pyroxene has been converted to actinolite and biotite, their feldspar have in some cases been albitized, and in places they have been swamped in end-stage quartz and heavily mineralized. Figures 5, 6, and 7 illustrate some of these changes.

One of the curious results of the conversion of pyroxene to actinolitic hornblende is exhibited in the powerful penetrating capacity developed by the uralitized pyroxene, since it is commonly found in an aggregate of acicular crystals which frequently penetrate the adjoining feldspars in every direction; soda seems to have been added during the process, derived undoubtedly from the soda-enriched liquid residuum responsible in part for the conversion. In some cases sufficient soda has been acquired by the uralitized pyroxene to cause the production of a blue amphibole of about the quality of glaucophane (norite from the Creighton Mine).

All stages of flooding with the end-consolidation, more siliceous, aqueo-igneous concentration-product may be seen, the maximum

[1] H. L. De Launay, *Contributions a L'Etude des Gites Metalliferes*, 1897, p. 25.

effects producing the so-called "micropegmatites," which are essentially the consolidated "concentrates" themselves—the "acid" differentiate of the more basic portions of the magma. These rocks consist of alkalic feldspars, biotite and hornblende, engulfed in a matrix composed of a micrographic intergrowth of quartz and alkali feldspar, which sometimes comprises 50 per cent of the rock.

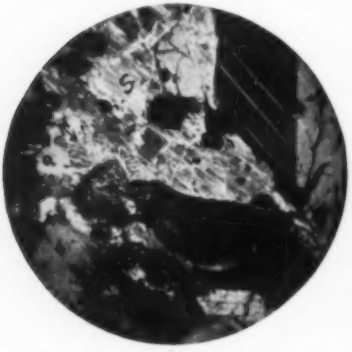

FIG. 5

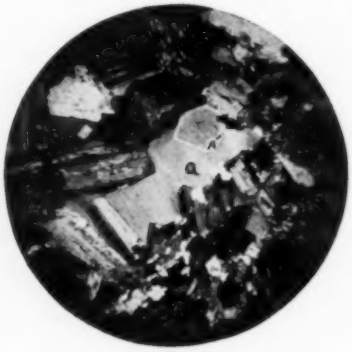

FIG. 6

FIG. 5.—Photomicrograph of norite from the Sudbury region, near Windy Lake, Ontario. Nicols crossed, magnification 20 diameters. The orthorhombic pyroxene here has been almost wholly converted to serpentine (Bastite) (*S*). A small amount of end-stage quartz (*Q*), in places mixed with feldspar in micrographic intergrowth (*M*) is usually associated with, or in proximity to, the serpentinized pyroxene. The feldspars in this facies of the norite have been but very slightly affected by hydrothermal attack, carrying very sparingly distributed small patches of sericite here and there.

FIG. 6.—Photomicrograph of norite from the vicinity of the Blezard Mine, Sudbury region, Ontario. Nicols crossed, magnification 20 diameters. Carrying considerable end-stage quartz (*Q*) and showing albitization margins (*A*) on some of the feldspar. The orthorhombic pyroxene has been almost wholly converted to pale green actinolitic hornblende, grading into biotite in places, remarkably ragged and patchy, and penetrating the feldspar in many places.

The biotite has been changed to chlorite, at times spherulitic; the hornblende is actinolitic in character, suggesting derivation from some other original.

In places the quartz increases in quantity so that it forms large groups of crystals of considerable area, but related nevertheless to the very end-stages of consolidation, judging from its structural relations to the other minerals. The phenomena described may all

be connected with late-stage crystallization; the coarsely micrographic matrix, which has the general characteristics of a quartz-feldspar eutectic, the chloritization of the biotite and "actinolitization" of the hornblende (or the uralitization of an original pyroxene) are all products of the activity of a solution-residuum formed in relatively large quantities during the selective crystallization of a much more basic magma. Figures No. 8 and 9 are illustrative

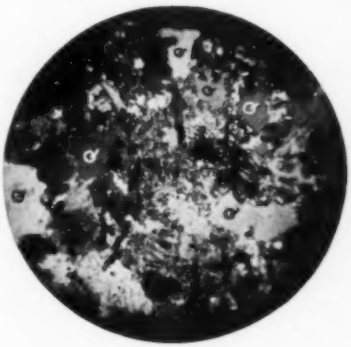

FIG. 7

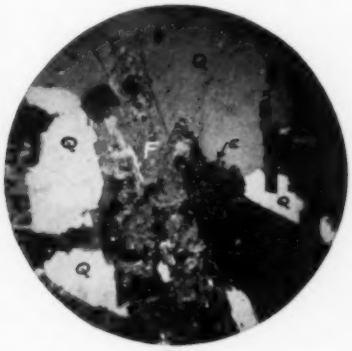

FIG. 8

FIG. 7.—Photomicrograph of norite from the Creighton Mine, Sudbury, Ontario. Nicols crossed, magnification 20 diameters. Swamped in end-stage quartz (*Q*) which in places had flooded the rock. The original orthorhombic pyroxene almost wholly uralitized and reorganized; considerable soda has been added in the processes so that in places a blue amphibole of about the quality of glaucophane has been formed, grading into the commoner green actinolitic hornblende. This rock has been more profoundly affected than the one shown in Figure 6.

FIG. 8.—Photomicrograph of micropegmatite from the acid margin of the nickel eruptive, Sudbury district, Ontario. Nicols crossed, magnification 20 diameters. Showing quartz in large crystal units (*Q*), albitized feldspar (*F*), and spherulitic chlorite (*C*), derived from biotite. The character of the rock is dependent on end-stage crystallization processes.

of this particular phase of late-stage crystallization. Both are "micropegmatites" from the Sudbury region, taken from the acid border of the nickel eruptive.

Figure 8 shows the larger crystal units of quartz flooding earlier feldspar, which has been albitized, and spherulitic chlorite, derived from biotite. Figure 9 shows the coarsely micrographic intergrowth of feldspar and quartz; the ferromagnesians have

been similarly affected, with the production of acicular green hornblende.

The action of end-stage emanation products on rocks which igneous masses have invaded may be even more extensive and profound. The extent and magnitude of these metamorphic changes depend upon the character of the rocks intruded and upon the quantity and quality of the emanation products themselves.

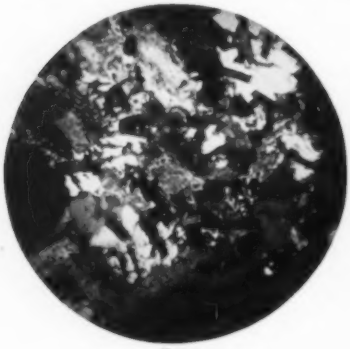

FIG. 9

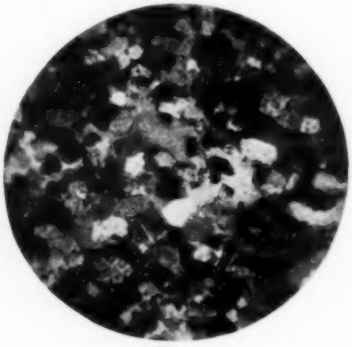

FIG. 10

FIG. 9.—Photomicrograph of micropegmatite, Levak Siding, near Windy Lake, Sudbury district, Ontario. Nicols crossed, magnification 20 diameters. Showing coarsely micrographic intergrowths of end-stage crystallization. Actinolitic hornblende in center, passing into chloritic aggregates.

FIG. 10.—Photomicrograph of arkose, adjacent to the Palisades diabase, about four miles south of Alpine. Nicols crossed, magnification 20 diameters. The "detached," or slightly separated (not all of the grains are as distinctly separated as here shown, however), and more or less reorganized and original clastic grains of feldspar are shown set in a matrix of coarser unit grains of mosaic-like quartz. The dark or black areas are quartz units in the position of extinction.

All of the contact phenomena are directly related to the action of magmatic end-stage emanations which produce a bewildering series of silication, sericitization, chloritization, epidotization, carbonatization, silicification, garnetization and metallic-mineralization effects whose origin and significance were recognized long ago by Lindgren, Kemp, Spurr, Berkey, and many others, and which are beyond the scope of this paper to discuss.

It has not been generally recognized, however, that such enormous quantities of quartz and feldspar may be concentrated by the

crystallization-differentiation of batholithic masses as to serve as carriers for magnetite, and to act at the same time as granitizing agents and producers of magnetite-ore bodies.[1] In these cases the country-rock may be so flooded with quartz, or quartz and feldspar from igneous sources, as to profoundly change the character of the invaded rocks without causing any of the phenomena just mentioned to ensue. As an example of this action on a very small scale, the effect of the intrusion of the Palisades diabase on some portion of the adjacent arkose may be mentioned. The original clastic grains of feldspar seem to have been detached and in small part recrystallized, the original grains of quartz appear to have been merged with and taken into the substance of the invading end-stage quartz derived from the igneous mass itself, so that the feldspar grains of the arkose are set, in a sort of poikilitic fashion, in a matrix of much more coarsely crystalline quartz behaving as a mosaic of larger unit grains. An attempt has been made to show this in Figure 10.

In connection with the magnetite ore-bodies of southeastern New York, there is an occurrence of extremely coarse and very acid granite, always intimately associated with the ore-bodies and usually best and most extensively developed immediately adjacent to them. Field and petrographic study shows that these "granites," which the writer has called Pochuck granite, are merely end-stage quartz, with in some cases feldspar, carrying partially assimilated fragments of the country rock (Pochuck-Grenville), and representing the very extreme end-phase product of the same general processes which produced the magnetite. Figures 11 and 12 illustrate two of them; Figure 11 is from the vicinity of the Clove mine, Figure 12 is adjacent to the Forest of Dean Mine, Orange County, New York. Both samples were taken at the surface. It will be observed that they are very largely quartz with a few scattered, partially assimilated fragments of country-rock (Pochuck-Grenville). Where the Pochuck-Grenville was more calcareous, and especially where the emanations encountered actual interbedded limestone (Grenville), characteristic lime-contact minerals were formed, although the interbedded limestone itself may have

[1] R. J. Colony, *The Magnetite Deposits of Southeastern New York.* To be published as a bulletin of the New York State Museum.

been totally destroyed. Such relations are shown in the old Mahopac, Tilly Foster, O'Neill, Forshee, Redback, Standish, Croft, and Todd mines in Orange and Putnam counties, New York.

It seems evident, therefore, that the injection of an igneous mass into pre-existing rock, and its subsequent consolidation, sets into motion physical and chemical processes which produce a

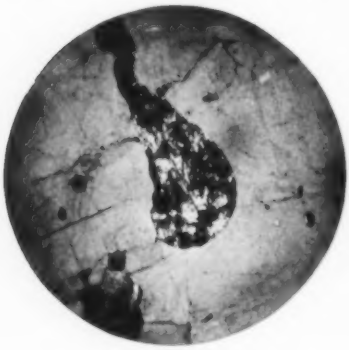

FIG. 11

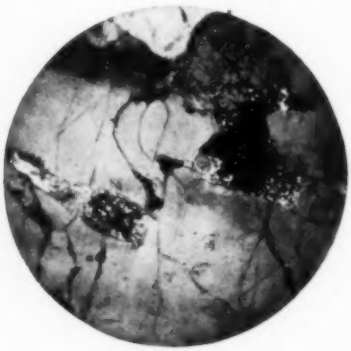

FIG. 12

FIG. 11.—Photomicrograph of Pochuck granite, Clove Mine, Orange County, New York. Nicols crossed, magnification 20 diameters. The gray field is a large unit grain of quartz. Swamped in the quartz is a serpentinized remnant of Pochuck-Grenville, consisting of an orthorhombic pyroxene with attached and sericitized feldspar. Practically all of the minerals other than quartz are simply remnants of partially assimilated fragments of like type, all profoundly affected by the magmatic end-stage aqueo-igneous solutions which gave birth to the quartz.

FIG. 12.—Photomicrograph of Pochuck granite, Forest of Dean Mine, Orange County, New York. Nicols crossed, magnification 20 diameters. An extremely coarse, grayish-white granite made up of end-stage quartz and feldspar with partially assimilated fragments of Pochuck-Grenville. The gray field is quartz, the fragments are remnants of country rock.

startling array of progressive changes,[1] both in the parent body and in the rock invaded. In many cases the effects are profound and of the utmost economic importance, since not only are most metalliferous deposits connected directly or indirectly with such processes, but many substances used in the arts and industries have their origin in the same sources.

[1] A recent article by Bowen on the behavior of inclusions in igneous magmas, which appears in a supplement to *Journal of Geology*, No. 6, Vol. XXX (1922), deals with some of the changes, which are explained on the basis of the "reaction principle."

A VENERABLE CLIMATIC FALLACY

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Warm climates within the polar circles and glacial climates on the borders of the tropics are justly regarded as the most outstanding features of geologic climates. That these contrasted climates should have intervened between one another to form an oscillating series adds a feature of the first order of significance. The glaciations on the borders of the tropics seem at first thought the more remarkable, and perhaps they are so, but when it is considered that five miles of ascent brings a greater fall of temperature than a change of 3,000 miles in latitude, there is reason to raise the question whether the transfer of low-latitude warmth to high latitudes is not after all the weightier feature. However this may be, mild climates in high latitudes are features of the highest order of interest.

Now for more than half a century it has been widely maintained that an extension of the sea would at least help explain the mild climates in high latitudes, if indeed it would not furnish a full explanation. In addition to this particular application, the doctrine that sea extension contributes to warmth of climate has found many other expressions in geologic literature.

This habitual association of warmth with sea extension seems to have grown out of the earlier view that in primitive times a warm ocean covered the whole earth. Starting with this concept, the differentiation of climates was held to have grown gradually out of universal warmth by general cooling attended by the emergence of the land and the reduction of the sea surface. The association of the sea with warmth and the land with lower temperature was natural under these assumptions.

When the study of the widespread phases of glaciation began—about a century ago—a general extension of glaciation was only

known to have occurred at a late geological period, and so it was natural to assign it to an advanced stage of cooling of the earth. Further, it was seen to be correlated with the great deserts and so the phenomena of glaciation and of great aridity were thought to be but the signs of a senile planet; the advance stages of the final drying up and freezing up of the earth. Thus the sea and warmth were habitually associated in geologic thought about the earlier ages, while dryness and cold were close companions in the thought of the later stages.

Who first advanced the special doctrine that the mild climates of the geologic ages in high latitudes were caused by an extension of the sea, it would be venturesome to state. Very likely it grew up gradually by little transfers of the earlier thought of a universal warm sea to the special cases of warm climates in high latitudes as evidences of these came successively into notice. At any rate, if the doctrine is to be put on the shelf, it is perhaps just as well not to lay stress on its parentage or on its clientele. It was a common doctrine, and quite unchallenged, when I first became interested in paleoclimatic subjects; I accepted it as standard doctrine and taught it. It was only when I had occasion to inquire seriously into geoclimatic problems that doubt as to its verity arose.

To avoid ambiguity let it be noted at the outset that the question here raised is specific and definite. Would an extension of the sea in high latitudes cause or tend to cause a warm climate *in and of itself irrespective of superimposed factors*? Of course the extension of a *warm* sea would favor a warm climate, and the extension of a *cold* sea, a cold climate. Our question is whether the replacement of a normal land surface by a normal sea surface in the high latitudes would thereby, irrespective of special conditions, tend to give a warmer climate. Let us first look for concrete evidence, and later turn to the theory of the case.

COMPARISON OF THE CLIMATES OF THE WATER-HEMISPHERE WITH THOSE OF THE LAND-HEMISPHERE

The distribution of sea and land is fairly well suited for this inquiry. The Southern Hemisphere is very largely covered by the ocean; its land surface is not only much smaller than the sea

surface, but is divided into tracts so well separated from one another and so nearly surrounded by the sea that they show the sea's normal influence. There is only just about enough land to bring out the normal effects of the sea influence satisfactorily under present conditions.

The Northern Hemisphere, on the contrary, has more nearly equal areas of land and of sea, but there is a distribution of these that helps us in distinguishing their individual influences. Viewed from the North Pole, the center of cold of this hemisphere, the land is seen to surround it in the form of a great triangle of which Africa and Asia form the base and North America the apex. Most of what sea there is in the Northern Hemisphere lies outside this triangle and in two parts, the North Atlantic and the North Pacific. The North Pacific is broadly connected with the South Pacific and may be regarded as an outlying adjunct of the water hemisphere on the south.[1] The connection of the North Atlantic with the South Atlantic is much narrower and their relations much less intimate, for the protruding eastern angle of South America splits the equatorial current and measurably differentiates the two oceans. The North Atlantic is very much more nearly surrounded by land than the North Pacific and its mean temperature is also higher than that of the other oceans.

Into the triangle of land about the North Pole there penetrate several offshoots or dependencies of the main oceanic bodies. These are land-girt in varying ways and degrees and these relationships help to show the climatic effects of certain special relations of land and sea, as will appear later. The dependencies of the North Atlantic connect it with the North Polar Sea—scarcely worthy of being called an ocean—which immediately surrounds the North Pole.

Comparison of the hemispheres as a whole.—As is well known, the Southern or Oceanic Hemisphere has a distinctly cooler and more inhospitable climate than the Northern Hemisphere, in which land is a much larger factor. This may be verified to any desired degree

[1] The North Pacific is always included in the technical "Water Hemisphere." This stands oblique to the climatic zones and on that account cannot well be used in a brief comparison of climatic hemispheres.

by specific comparisons of the temperature charts, the positions of the isothermal lines and the distribution of life. The general import is most conveniently indicated by the fact that the *thermal* Equator lies 5° or 6° north of the geodetic or geographic Equator. Krümmel estimates the average surface temperature in the Northern Hemisphere to be 19.20° C., that in the Southern to be 15.97° C.; while the air temperature averages 15.1° C. for the Northern Hemisphere, and 13.6° C. for the Southern.[1]

For the purposes of this discussion, the nature and distribution of life furnish better criteria than simple temperatures, since the evidences of past climates rest almost wholly upon the fossil life, and anyway life is a composite index of climate—a natural correlation as it were—while temperature is only one factor. For brevity, then—as well as its comprehensive significance—life, especially human life, will be used mainly in the following comparisons. Human life implies the concurrent presence of a highly complex series of supporting types of lower life, both vegetable and animal.

COMPARISONS ON SELECTED PARALLELS OF LATITUDE

To sweep the full range of the high latitudes, let us begin our comparisons with the parallels of 50° on each side of the Equator. Let us begin also at the most typical spots. The Indian Ocean has a form and a placement specially well suited for showing whatever warming effects in mid-latitude a great expanse of sea may have. Its northern edge reaches 20° beyond the Equator and thus brings in from the Northern Hemisphere a large section of equatorially warmed water, while the southern edge falls more than 20° short of the South Pole and thus excludes a large area that might otherwise contribute polar waters. Furthermore the Indian Ocean is broad and roughly rotund. Its connections and relations are simpler than those of the other great oceans. Let us then start our comparisons with an island lying centrally in this highly representative ocean. Kerguelen Island lies a little on the equatorial side of 50° S. Lat. (48°39′ to 49°44′), in the very heart of this ocean, far away from any other land of moment. It is more than 2,000 miles from Africa and a little farther than this from Australia; it is more

[1] Cited from *A Textbook on Oceanography*, by J. T. Jenkins, London, 1921.

than 1,000 miles from the nearest known land to the south and 3,800 miles from the nearest land on the north. It is therefore typically oceanic. The severity and sterility of its climate are so pronounced that it stands as a type of inhospitality. Its mean temperature is only about 39° F.(4° C.). Bearing directly on the question here at issue, the *Encyclopedia Britannica* says: "Its temperature is kept down by the surrounding vast expanse of sea." Relative to its discoverer, Yves Joseph de Kerguelen Tremaric, it further says: "He was one of those explorers who had been attracted by the belief in a rich southern land, and this island, the South France of his first discovery, was afterwards called by him, 'Desolation Land' in his disappointment."

For comparison with this southern land of desolation in the heart of a typical ocean, let us follow the same meridian to the same latitude in the Northern Hemisphere. It leads to a point in Central Asia, the heart of the earth's greatest continent, and is thus admirably adapted to our purpose. The comparison point lies about 350 miles south of the Trans-Siberian Railway. The region has long been inhabited and has played a notable part in human history. In its habitability, it is in strong contrast with Kerguelen. The region habitable for man in the Northern Hemisphere extends about 1,400 miles farther north, while no human habitation lies between Kerguelen and the South Pole or would probably lie there if more islands lay between to furnish sites for settlements.

Now, taking these two contrasted stations as key points—Kerguelen as representative of oceanic conditions, and the corresponding point in Central Asia as representative of continental conditions—and following the parallels of 50° around the globe, we may gather a generalized view of the climatic effects of sea and of land, respectively, just above mid-latitude. Starting in Central Asia and following this parallel westward, we find that nearly half the great capitals of Europe lie north of it, viz: Moscow, Warsaw, Prague, Berlin, Stockholm, Christiania, Copenhagen, The Hague, Brussels, and London. Let it be granted without reserve that the western border of Europe is much affected by the warm currents of the Atlantic; but in consistency it must be equally noted and emphasized that this is *a special effect of a special part* of an ocean;

not its normal mean effect, and that there is *a similar special effect of the opposite kind* on the opposite side of the Atlantic. Such special effects largely offset one another in combining the enhanced warmth of the eastern sides of the Atlantic and Pacific oceans with the lower warmth of their western sides to get the mean for the whole parallel.

Following the 50° parallel onward across America, it is found to traverse the settled lands of Newfoundland, Quebec, Ontario, Manitoba, Saskatchewan, Alberta, and British Columbia, leaving the capitals of the first three and last on the south, and the capitals of the remaining three on the north. On the cold side of the Asiatic continent, the parallel traverses Sakhalin, the lower Amur region, Manchuria and Mongolia, to our starting point in Central Asia. Chita, Irkutsk, Tomsk, Omsk, Tobolsk, and other important cities, lie north of the parallel even in this eastern and colder part of the continent. From almost all points in this circuit of the globe human settlement extends 1,200 to 1,500 miles north of the 50° parallel, while the highest northern permanent settlement lies nearly 2,000 miles north of it.

Returning now to Kerguelen, for a similar circuit of the globe in the oceanic hemisphere, the first and almost only land traversed is southern Patagonia, a region of well-known inhospitality of climate and scantiness of population. The bleak little port of Puntas Arenas is almost the only town of note south of the 50th parallel in its entire circuit. The hard lot of the Tierra del Fuegans has become proverbial. The Falkland Islands lie only 1° to 3° south of the 50th parallel, and yet they show no signs of *aboriginal* inhabitants. Sea products and sheep raising have drawn to them about 2,000 Europeans and South Americans. The small islands of Auckland, Campbell, Macquarie, and Emerald, south of New Zealand near 60° S. Lat., seem to show some special effects of the warm return current of the South Pacific, but still they have rather severe climates and are only inhabited by a few sheep raisers. Taking the southern oceanic circuit as a whole, its climate is strikingly more severe than that of the northern more largely continental circuit.

Comparison of the oceanic and terrestrial 60° belts.—Advancing 10° poleward, it is to be noted that the parallel of 60° S. Lat. is practically oceanic throughout; it crosses no appreciable land. It traverses the southern portions of the Atlantic, Pacific, and Indian oceans and these portions have broad connections with the corresponding tropical portions, affording free facilities for a normal distribution of oceanic influence. Notwithstanding this, the belt is one of prevailing ice floes. The mean temperature at the surface is practically O° C., and the climate very severe. Such life as appears at and above the surface seems to be chiefly that which lives directly or indirectly on the minute life brought to the region by *under currents* of the ocean. Such life is not therefore a direct index of the local climate. *There are no permanent human settlements on any island in this belt or on any lands within it.*

Quite in contrast to this oceanic parallel, the parallel of 60° N. Lat. lies chiefly on land. It however crosses the Atlantic, where narrowed at the north, touching the very apex of Greenland; it also crosses Behring Sea, a dependency of the North Pacific. It is inhabited by man in practically all its sections. It shows rather markedly the local effects of the warm currents of the ocean in raising the temperature on the east sides of the water bodies and of the cold currents in lowering it on the west sides. But even in Siberia, where the oceanic influence is unfavorable or remote, Vivninkskoe, Ust Maiskaya, Olekminsk, and Repolovskoe lie on or near the 60th parallel, while many settlements lie farther north. Following the parallel westward from Siberia, we reach Petrograd before much effect of the warm Atlantic currents is felt. Farther on, Helsingfors and all the settlements of Finland lie north of this parallel, while Upsala lies just south of it and much the larger part of Sweden lies north of it. Christiania is almost on the 60th parallel, while nearly all Norway lies north of it. The Scandinavian peninsula shows markedly the effects, not of "the ocean" in an unqualified sense, but of *the warm currents of the east side of the ocean.* This effect is offset, on the west side, by the Labrador Current, which gives rise to corresponding depressive effects. These latter are just as much effects of "the ocean" as are those of the Gulf Stream.

Even on the Labrador coast, Sangmijok lies just north of 60°, while in the interior numerous native villages and traders' stations lie near and north of this parallel. On the western coast of the American continent, which again is affected by *warm* ocean currents from the Pacific, there are busy towns and active human industries on or north of this parallel, such as Seward, Cordova, Valdez, and not a few others.

Thus the climate of 60° N. Lat.—equating the favorable and unfavorable effects of particular ocean currents—is very markedly more hospitable than that of the oceanic parallel of 60° S. Lat.

Comparison of the climates at the Arctic and Antarctic Circles.—The Antarctic Circle fits the Antarctic land much as a hoop fits a barrel. If the simple fact that a broad sea surrounding a relatively small land were sufficient to induce figs and magnolias to grow within the polar circles, it would seem that the sea-girt coasts of Antarctica should furnish an illustration, all the more so because the encompassing seas have broad connections with the tropical tracts of the Pacific, Indian, and Atlantic oceans. As a matter of fact, the climate of this sea-girt coast is extremely severe, as is too well known to require any special statement.

The Arctic Circle, on the other hand, lies on the ring of land which surrounds—with some interruptions—the Arctic Ocean, or, more truly, the North Polar Sea. It traverses land nearly all the way round, and great continents lie to the south, while an ice-covered sea lies within it. Scarcely 15 per cent of the Circle is occupied by arms of the sea. And yet, in contrast with the inhospitality of the Antarctic region, human settlements, and the lower life necessary to support these, are located in practically every segment of the Circle. Even in Siberia, where the conditions are most continental and where the adjacent seas are of the specially cold order, Sredne Kolymsk, Verkhoynsk, Krasnoe, Zashiversk, Shigansk, and Obdorsk lie on or near the Circle and not a few other settlements lie still farther north. Not a little of Siberia even at this high latitude is covered with coniferous forests.

Following the Circle on into Europe, we find lying on or near it, Kemitrask, Rovoniemi, Turtola, and Silbojock. It is of some special significance that near Vuollerim the Arctic Circle *is crossed*

by a railroad, while settlements extend nearly 300 miles farther north. In this region, however, the *warm* currents of the Atlantic have very considerable special effects. Iceland, the home of a creditable civilization, lies only a little south of the Circle in the midst of the narrowed portion of the Atlantic. The climate of east Greenland is notably depressed by an ice-bearing ocean stream that hugs the eastern coast, but on the western side, facing Davis Strait, the Arctic Circle cuts across the Danish colony, passing between the two capitals, Godhaab and Godhavn. This region, which has special interest from the climatic point of view, will be discussed more at length in a later article. In crossing North America, coniferous forests, native settlements, and traders' stations are encountered. The western coast is reached between the settlements Kalzebue and Kawalik, not far north of Nome.

Taking this whole land circuit together, it appears that after balancing the effects of warm currents against those of cold currents, the climatic picture stands in distinct contrast to that of the sea-girt coast of Antarctica.

Within the Polar Circles.—Within the Antarctic Circle nothing but severity and inhospitality of climate prevails. Such large living animals as inhabit the region live almost exclusively on sea-food brought to the Antarctic coasts by undercurrents of the sea and take on forms peculiarly adapted to this subsistence on imported food and to the severity of the climate.

The climatic import here, however, is confused by complications, and must be taken with some reserve on account of this. The area within the Antarctic Circle is chiefly land, while the area without is sea. The area within is not only land, but exceptionally elevated land, on the average, so far as known, and this elevation introduces a special factor which may be as important or even more important than either sea or land independent of elevation.

Within the Arctic Circle, the conditions are also peculiar in that a *frozen* sea occupies the center, surrounded by a ring of land broken by sea gaps. A frozen sea in such high latitude is almost constantly covered by snow, as is the land part of the season. A normal comparison of water surface with land surface is scarcely possible. Within the North Polar Circle, however, there is indige-

nous life developed into rather ample chains of dependent life, some of the chains being based on land plants, and some on sea plants, the former rising to the grades of hares, ptarmigan, reindeer, and the foxes and other animals that prey on these, while the latter rise into the much more complex and ample chains of sea life, ranging up to walruses, whales and Eskimos. These are pretty well scattered around the Circle but on the west side of Greenland in a land-girt region there are two limited areas of exceptional mildness of climate and remarkable abundance of life, constituting veritable climatic oases in the frigid desert of the north. These have a very significant story to tell which will be taken up in a later article.

Let us inquire whether theoretical considerations tally with the array of facts brought out by the foregoing comparisons.

THEORETICAL CONSIDERATIONS

To secure brevity, these may be put in the form of affirmative propositions.

1. *Water surfaces reflect more insolation than land surfaces.*—The surface of water is normally smooth and close-grained, so that it has much the effect of a polished surface and is highly reflective. In the high latitudes the angle of incidence of the solar rays is always low and for the larger part very low, and this gives a high percentage of total reflection from the water surfaces. The surface of the land, on the other hand, is rough and granular, so that it is highly absorptive; it closely approaches the theoretical "black body." The vegetal clothing of the land is also rather highly absorptive, due to a selective adaptation to meet the absorptive requirements of vegetal life. The combined effect is to render the land surface much more highly absorbant of solar rays than the sea surface.

2. *Water surfaces lose more heat by evaporation than land surfaces.*—The annual evaporation from sea surfaces is greater than that from the land surface, even though it is a few degrees lower in mean temperature. As a result less of the heat absorbed by the land takes the latent form and ceases thereby to have a heating effect. These differences are qualified, however, both pro and con, by the formation of surfaces of ice and snow on both land and sea. These surfaces are highly reflective and only slightly evaporative.

3. *The heat energy rendered latent by evaporation is carried across the climatic zone in a relatively ineffective form.*—Climate in the common sense of the term relates to the horizon occupied by living things. For convenience in this discussion we may regard the climatic zone as that between the earth's surface and the clouds. The heat energy rendered latent by evaporation crosses this zone embodied in vapor in a non-heating form. It only returns to a heating form when the vapor is condensed into cloud. When condensed into cloud, about half of the heat that returns to the sensible form is radiated outward and is lost; about half is radiated toward the earth and helps to compensate for its previous inertness. But the cloud itself interposes a highly reflective screen between the sun and the earth; a large percentage of the insolation is thus turned back to the sky without passing through the climatic zone or reaching the earth's surface at all.

There is some compensation, however. The vapor in rising from the surface across the climatic zone is a good absorber and re-radiator, especially of the "dark" rays from the earth. Over the sea this is only brought to bear on the lesser radiation sent forth from the cooler sea surface. On the other hand, the heat sent back from the land crosses the climatic zone more largely in the sensible form and is more largely absorbed in the passage and is repeatedly re-radiated.

While these considerations are not exhaustive, they sufficiently show that *a water surface in high latitude is a cooling agency.*

There is a simple mechanical consideration that deserves passing notice also:

4. *An increase of sea-room in which the warm equatorial currents may spread and cool themselves in intermediate latitudes, reduces their effectiveness in high latitudes.*—The effectiveness of the oceanic waters in conveying warmth to the polar regions is obviously dependent on the conservation of the heat received in low latitudes, during its long passage to the high latitudes. The more these warmed waters are spread out in their passage from the low to the high latitudes, the earlier will their heat be dissipated and the feebler their effects in the very high latitudes. It is quite clear that if the continents did not concentrate the tropical waters of the Atlantic

into the Florida Current (Gulf Stream) and similarly the tropical waters of the Pacific into the Japan Current, and by so doing restrain their spreading in their journey to the north, they would fail to raise the temperature of any given area in high latitudes as effectively as they do now. On the other hand, if the warm waters from the low latitudes are concentrated into deep streams by convergent lands, or better still if they are forced to flow poleward as deep currents protected from surface agitation by winds and from the radiation enhanced by these winds, they will be more effective carriers of heat to the high latitudes.

While some other theoretical considerations might be added, the foregoing confirm the inductions drawn from the preceding comparisons and give them great cogency. Observation and theory together make a clear and decisive case. The conclusion may therefore be drawn with great firmness that *extension of sea in high latitudes, in itself considered, normally renders the climate cooler than it would be if no extension took place.* It is to be scrupulously noted that this conclusion applies simply to the alternative of sea and land, not to special influences super-added on either side, such as warm currents, on the one side, or cold currents and great elevations of land surface, on the other. These super-added features are of course to be dealt with on their own account as special influences arising from super-imposed causes.

While the evidence is thus decisive against the assumed warming effects of sea extension in itself, a study of the evidence makes it clear that the ocean is a very effective climatic agency *both* in *raising* and in *lowering* regional temperatures in response to co-operating conditions.

This influential action has two phases that are to be distinguished in the study of geologic climates: (1) transient effects, and (2) secular effects. It is obvious that the superficial effects of the ocean are transient because the resulting temperature of the air is soon changed by radiation and the moisture supplied to the air is soon precipitated. If an effect is to be perpetuated by these means there must be a constant *renewal* of the activity. On the other hand, a prolonged effect may be produced by the great capacity of the ocean to store and retain heat, and this stored heat may be trans-

ferred from one latitude to another by the slow creep of the deeper waters of the ocean. This high capacity for heat storage and for slow transfer calls for serious consideration in the study of secular changes of climate. Its high value makes the ocean an important factor in the explanation of geologic climates; but only a factor.

THE GREAT HEAT-STORAGE CAPACITY OF THE OCEAN

(1) As is well known, the specific heat of water is roundly about five times that of average rock-substance. (2) The area of the deep ocean—neglecting the shallow waters of the continental shelf—is roundly twice that of the continental areas. (3) If we allow that the secular heating and cooling of the land areas—say such as takes place in changing to and from a glacial period—reaches 1,200 or 1,300 feet deeper under the land than under the sea before it is counteracted by internal heat (which seems, from such data as we have, an over-generous allowance), the depth subject to secular change of temperature under the ocean surface is roundly ten times that under the land surface by reason of the mobility of the water. Combining these, the thermal potency for secular thermal effects is $5 \times 2 \times 10$ in favor of the ocean considered as a climatic influence. This great secular potency is to be combined with the much more transient potency of surficial action in reaching the total influence and the combination will sometimes be additative and sometimes subtractive.

In this article the choicest bit of evidence that simple sea extension is not a controlling factor has been passed over with little more than mention, and left for consideration in another article, because, in the first place, it was not necessary for the support of the main proposition and, in the second place, because it forms an admirable introduction to the consideration of the storage capacity and carrying power of the ocean. Starting with the existing status, it forms, a first step in the study of the secular effects of the ocean on climate. It prepares the way for passing from the present long-time, long-distance action of the ocean to the greater effects of like kind that obtained at intervals during the geologic ages.

THE RED BEDS OF THE FRONT RANGE IN COLORADO: A STUDY IN SEDIMENTATION

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Aim of this article.—The term "Red Beds," as used in this article, needs some definition. The term includes only those Colorado formations known as the Fountain, Lyons, and Lykins series and their accepted time-equivalents east of the Continental Divide. These beds lie unconformably on pre-Cambrian granites and gneisses,[1] occur more or less continuously from Wyoming to New Mexico, and have an undetermined extension eastward from about longitude 105° W. They are tilted, often to angles of over 60°, the direction of dip being southeast to east. The present paper is not concerned with their age, already established by Henderson,[2] the Fountain and the Lyons as Pennsylvanian, the Lykins as Permo-Carboniferous in its lower part, Triassic (?) in its upper part. Rather, the paper aims to contribute to the literature of sedimentation by (*a*) fully describing the beds and (*b*) discussing both the conditions under which the sediments were laid down and the paleogeography at such times. Though the writer is familiar with the "Red Beds" of the Black Hills, of the Bighorn uplift, of the Laramie region, and of southeastern Colorado, the conclusions are based chiefly on a two years' study of the stratigraphy from the Cache la Poudre River, about 16 miles south of the Wyoming line, to Canyon City, west of Pueblo.

THE FOUNTAIN FORMATION

Description.—It is difficult to give a typical section for the Fountain formation because of its great lateral and vertical varia-

[1] At Canyon City the beds lie unconformably on Mississippian limestone and overlap on Ordovician limestone.

[2] J. Henderson, "The Foothills Formations of North-Central Colorado," *Colo. Geol. Surv., Bull. 19* (1920). Earlier discussions are chiefly by N. M. Fenneman, "Geology of the Boulder District," *U.S. Geol. Surv., Bull. 265* (1905), and R. M. Butters, "Permian or Permo-Carboniferous," *Colo. Geol. Surv., Bull. 5* (1913).

tion. Yet the following section, made 500 feet north of Gregory Canyon, west of Boulder, fairly represents the beds in the strip from Cache la Poudre River to Canyon City.

	Lyons Sandstone, Conformable (?) upon	Feet
u	Arkose to conglomerate, massive, reddish, cross-bedded (torrential); pebbles qz. and orth., the former subangular to well rounded, and up to 3 in. in diameter, the latter chiefly angular cleavage fragments; also granite and pegmatite pebbles, and muscovite flakes ⅜ in. long; iron stained, slightly calcareous arkosic matrix; breakage across pebbles	35
t	Sandstone, chiefly massive, traces of ¼-in. to 2-in. beds; red, with areas leached to gray and with greenish perfectly rounded ½-in. fragments of arkose apart from leached areas; hard, fine-grained, slightly calcareous, ferruginous (ferric iron); breaks to angular blocks and varies laterally to arkose	10
s	Arkose, massive, dark, pink, coarse—much as in bed *u*	10
r	Sandstone to arkose, red to whitish—much as in beds *t* and *u*	2
q	Sandstone, massive, red; fine grained, dense, firmly cemented (see also bed *t*)	3
p	Mainly covered; near top, various massive coarse arkose beds, cross-bedded; at about middle a massive 8-ft. arkose, with what may be laminations of varying coarseness; lower part much as upper, pebbles averaging 1 in. in diameter, not firmly cemented in an arkosic matrix	200
o	Partly covered; arkose in 3-ft. to 5-ft. beds, reddish or leached (?) to gray; fairly even-grained, subhard, grains averaging less than ⅛ in., but with pebbles up to 2 in.; arkose much as above, with thin beds of reddish shale, highly muscovitic, and thin beds of red sandstone, platy, muscovitic	92
n	Partly covered; arkose much as in bed *u;* arkose as above, with sandstone and shale (see also bed *t*)	90
m	Conglomerate, arkosic, massive, reddish—much as in bed *u*, with 2-ft. lenses of well-rounded, coarse gravel, containing granite and white qz. pebbles up to 3 in. in diameter	30
l	Sandstone, deep red to purple, seemingly massive but leached in streaks possibly parallel to obliterated bedding-planes (see also bed *t*)	5
k	Conglomerate, much as in bed *m*, torrentially cross-bedded	60
j	Shale (?), thinly and unevenly bedded, dark red; very arenaceous, with flakes of muscovite	3
i	Shale (?) as above, but evenly laminated	3
h	Sandstone, massive, dark red; fine grained, with muscovite flakes	5
g	Sandstone, massive but seemingly thin bedded (½ in. to 8 in. thick); see also bed *t*	7

f	Shale (?), thin bedded, reddish, arenaceous, muscovitic	2
	(biotite dacite porphyry sill)	25
e	Covered	50
d	Sandstone, much as in bed *t;* greenish arkose balls from lower beds, or else representing coarse sands long rolled about	10
c	Conglomerate, matrix arkosic, pebbles up to 8 in. in diameter, qz. and orth. preponderant, but much granite fine and coarse grained, of both biotite and hornblende facies; also rarer large limestone fragments, hard, crystalline, reddish; in nature much as bed *u*	75
b	Conglomerate, much as in bed *c*, but with lowest beds merely gritty to arkosic, and with many lenses of pebbles up to ½ in. in diameter	25
a	Shale (?) finely laminated, dark red; subhard, very arenaceous and ferruginous, somewhat calcareous	1
		718

(Unconformable on Granite)

Analysis of this section does not of course reveal the lateral variation in size of grain, a significant characteristic of the formation; beds wedge out and coarse grain gives way to fine, often in a few feet. It should further be mentioned that north of the Cache la Poudre River appear intercalated limestones, carrying marine fossils and becoming of increasing importance as the Wyoming line is approached. At Colorado Springs, also, some of the sandstone beds are grayish to greenish, and, 475 feet up in a 2,000-foot section, a marine fossil, *Lingulodiscina*, is found in a pocket of green shale.

Analysis does however disclose other salient characteristics of the Fountain formation, *all* which must be explained and harmonized in an interpretation of the sediments. The main characteristics are (1) absence, anywhere in the sequence, of the marine rhythm, conglomerate to sandstone to shale, or vice versa; (2) a consequent great thickness of unassorted, unsized conglomerate and arkose, with only occasional fine-grained arenaceous material; (3) a predominance of subangular and angular pebbles, often of bowlder size, and notable among which are muscovite flakes ¾ inch long,[1] fresh feldspar fragments, and bits of limestone; (4) freshness of the feldspar; (5) a peculiar type of cross-bedding, described below.

[1] N. M. Fenneman, *op. cit.*, p. 22, assumes that the muscovite is secondary. S. F. Emmons, *U.S. Geol. Surv., Monograph 12*, p. 68, had long before recognized it, under the microscope, as primary in large part.

Less significant, perhaps, are the red color, the presence of calcareous as well as hematitic and siliceous cement, and (except as above noted) the absence of fossils.

The cross-bedding is scarcely of a type recognized by the textbooks. The scale is medium, the cross-bedded horizons seldom occupying more than 2 feet vertically. In general, the dips are at low angles, though by no means always so, and run in all directions, both parallel to the dip of the true bedding, at right angles to it, and obliquely. The cross-bedded layers are truncated both by horizontal beds, as in "torrential" cross-bedding, and by other and highly irregular cross-beddings.

The thickness of the formation also has a bearing on its interpretation. At the Cache la Poudre, the thickness is 600–725 feet. Thence southward, the thickness is 900–1,075 feet west of Fort Collins; 1,000 feet at Lyons; 800–1,500 feet near Boulder; 500 feet at Morrison; 4,500 feet, at the maximum (the average being 2,000 feet), at Colorado Springs; 1,000 feet at Canyon City; 250 feet a mile south of the Arkansas River; 200 feet at a point 6 miles northwest of Badito. If Fountain beds are present in the Purgatoire Valley southwest of La Junta, recent well borings would indicate there a thickness of about 1,000 feet.

Interpretation of conditions of origin: the marine hypothesis.—As far as the writer knows, discussions of the origin of the Fountain sediments make them marine. The most complete interpretation is that of Fenneman (1905), accepted by Butters and George (1913) and by Henderson (1908)—though the latter (personal communication) is now in accord with the present writer. Fenneman's view, briefly, is this. In late Pennsylvanian time, a north-south shore line, of unstated length, existed 10 to 12 miles west of the present foothills of the Front Range. This land was of granite and of very low relief,[1] though, as Fenneman deduced from the absence in the Fountain sediments of "residual soil" material, the land was not a peneplain in the usual sense. On this "featureless" land, the sea encroached, its advance and resultant planation of the shore keep-

[1] N. H. Darton, *U.S. Geol. Surv. Prof. Paper 52*, p. 16, differs from Fenneman at this point, by emphasizing relief. Relief is certainly conspicuous on the "old plain," as now visible near Red Mountain, close to the Wyoming line.

ing pace with the disintegration of the granite under semiarid climatic conditions. The rock fragments were so rapidly buried in a constantly subsiding trough that they were little rounded or comminuted. Violent currents in the shallow sea produced the cross-bedding.[1]

Interpretation: the writer's river hypothesis.—Behind the marine hypothesis is the weight of tradition. Yet the hypothesis seems to have serious defects. Scarcely one characteristic of the beds suggests to a modern sedimentationist marine conditions; taken together, the characteristics almost irresistibly point to a continental origin. The lack of a marine rhythm; the thickness of the conglomerate or arkose; the lateral variation; the unsorted, unsized, angular material; the red color; the freshness of the feldspar; the type of cross-bedding—this combination emphatically indicates deposition by a river in a semiarid climate. The presence of *Lingulodiscina* at Colorado Springs can be harmonized with such a point of view.

Nor is such a point of view entirely a matter of theory. It has been checked by studies both of the Pliocene Nussbaum formation of eastern Colorado, admittedly of river origin, and of the sediments now being left in alluvial fans and on flood plains by Boulder, Clear, Big Thompson, Fountain, and other "creeks" debouching from the Front Range. The correspondence, except for color (a matter easily explained), is well-nigh perfect. Photographs were taken of Fountain sediments newly revealed in cuts at Golden and of modern flood beds exposed at Boulder in diggings. Pennsylvanian and modern sediments can scarcely be distinguished from each other.

By these studies, the origin of the cross-bedding in the Fountain, e.g., becomes manifest. In flood time, if not restrained by man, the present "creeks" would wander far from their channels, trespassing on each other's territory and confusing coarse and fine sediments. In fact, the Nussbaum "creeks" did so wander. The result, as

[1] N. M. Fenneman, *op. cit.*, pp. 54–57. Occasionally the suggestion is still met that the entire present Rocky Mountain area was submerged, the Fountain thus being an eastward extension of West Slope formations like the Maroon conglomerate. But the Maroon conglomerate is *finer* than the Fountain material, and surely such large bowlders as are common in the Fountain could not have been transported far.

evidenced in miniature floods, is the production of much "scour and fill" cross-bedding, which is of medium scale and parallel to the dip of the true bedding, as in the Fountain sediments. In addition, as the flood subsides, there arise little islands, separated by unorientated rivulets. The dip of deposits on these islands and temporary "shores" is at all angles and in all directions, even contracurrent, again as in the Fountain sediments.

Interpretation: climate and paleogeography.—Can the type of river sedimentation be further determined? It is believed that it can—by consideration of climatic and paleogeographic possibilities such as should not be ignored in modern studies. Almost certainly the climate can be set down as semiarid, with all that that implies. As to paleogeography, the marine hypothesis assumes, as has been said, that directly to the west of a shallow sea-trough lay land of unknown extent. The writer also thinks that the ancient Colorado rivers must have flowed from either the west, northwest, or southwest. The basis of belief is not the time-worn statement that the sediments are those which would have been derived from a granitic mass similar to that west of the present-day foothills. That argument is not convincing. But, if the sediments came from north of Colorado or east, they should have been coarser in those directions. To the east, Fountain material seems entirely lacking.[1] To the north, the presence of the intercalated limestones carrying marine fossils reveals a sea, strait, or bay in that direction.[2]

It is then quite possible that streams flowing almost east from a Paleozoic Front Range furnished the Fountain material; if so, the Fountain is an ancient Piedmont plain, with here and there alluvial fans higher than elsewhere, and with masses of sheet wash. The nature of the sediments fits in with this idea. Furthermore, since the Maroon conglomerate and other West Slope series seem

[1] In western Kansas, the Cimarron shale, 1,000 feet thick, lies unconformably on granite, but it would seem to correspond to Lykins material in Colorado. In any event, it is far finer grained than the Fountain; the same is true of what may be 1,000 feet of Fountain sediment in the Purgatoire Canyon south of La Junta (maximum size of pebbles 2 inches). See also N. H. Darton, on the Cimarron shale (Syracuse-Lakin folio, p. 2).

[2] The writer believes, because of studies made in Wyoming, that a strait connecting with a western sea lay between Colorado and a Wyoming land mass.

to be of much the same age as the Fountain formation, a late Paleozoic Front Range axis must have been continually rising in order to supply such a thickness of sediments. The induction is not out of accord with the present-day belief that the land mass of "Columbia" underwent marked elevation in late Mississippian time, nor with the view of Spurr[1] and others that rejuvenation of Colorado land masses occurred in early Pennsylvanian time.

It is here desired, however, to suggest another possibility—though by no means to cling to it. The thickness of the Fountain formation increases, in general, from Cache la Poudre River to Colorado Springs and then again decreases. It will also be recalled that in the Colorado Springs section *Lingulodiscina* occurs 475 feet above the base. Once, at least, there must have been an embayment here. It may be that, although the main axis of the late Paleozoic Front Range ran north-south, east-west spurs occurred north and south of Colorado Springs, these spurs acting as divides to rivers flowing northeast and southeast over whatever foreland stretched in their courses. Limestone pebbles in the Fountain near Boulder could not now be derived from the immediate west, and at Badito are found the largest bowlders (much larger than those at Colorado Springs) in the Fountain sediments. Only further and very detailed studies[2] can throw more light on the paleogeography of Fountain times, but at least such evidence as is attainable strengthens the river hypothesis.

THE LYONS FORMATION

Description: typical Lyons.—The typical Lyons sediments, though having the same strike and dip as the Fountain beds, have not quite the same distribution, and are not easily recognized

[1] J. E. Spurr, "Geology of the Aspen Mining Region," *U.S. Geol. Surv. Monograph 31*, p. 32.

[2] The Glen Eyrie shale, found only at Colorado Springs, needs closer attention. G. I. Finlay, "The Glen Eyrie Formation," *Jour. of Geol.*, Vol. XV (1907), p. 589, suggests that the Glen Eyrie shale lies unconformably beneath the "purplish-red sandstone," with "intercalated gray or light-pink arkose" with which the Fountain begins. The Glen Eyrie shale, however, is also of Pennsylvanian age, and its *Lepidodendron* flora implies swampy lowlands. The facts strengthen the suggestion that the Colorado Springs region at first marked an axis of depression rather than of elevation.

save from the Cache la Poudre River to Colorado Springs, but in this strip they are so homogeneous that a vertical section is unnecessary. Their contact with the Fountain is sharply defined, since they consist essentially of fine-grained red or pink to white sandstone, at times cemented to an orthoquartzite—a process still continuing. Under the microscope, the grains, except for a little comminuted feldspar and muscovite, are seen to be quartz, are notably rounded and uniform, and in diameter vary from 0.1 mm., or less, to 1 mm. The color is due to films of ferric oxide coating the grains. The thickness of the formation ranges from 850 feet at Colorado Springs to a few hundred feet north of Lyons. Other major characteristics important for interpretation are the type of bedding (including cross-bedding) and the occurrence of ripple marks and (rarely) of amphibian tracks. Of minor significance are beautiful dendritic markings due to manganese oxide and small, rounded cavities, marking spots where limonitic concretions have fallen out. Locally, as at Colorado Springs, a heavy conglomerate, with *rounded* bowlders 2 feet in diameter, occurs near the middle of the formation.

The significance of the true bedding is not that it is, to the casual glance, massive, or, when more carefully examined, either thinly platy or slabby, hence good for flagstones, but rather the fact that close scrutiny reveals that all the beds consist of laminae from $\frac{1}{64}$ inch to $\frac{1}{8}$ inch in thickness. These commonly alternate in light and dark bands (disguised by the general pink of the formation), the bands being minutely cross-bedded in uncertain patterns. Much more prominent is cross-bedding on such a scale that its interpretation always attracts comment. The true bedding now dips eastward at very steep angles, and in places between a 10- to 15-foot thickness of such slabs will appear an equal thickness of cross-bedding, abruptly truncated above and below, and *dipping eastward at an angle always less than that of the true bedding*. Nor is this all. Less conspicuous, but seldom lacking, is another set of large-scale cross-beds *dipping at present steeply westward*. A moment's reflection will show that, if the original dip of the beds were restored as a gentle eastward slope, the cross-bedding which now dips eastward would dip gently westward and that which now dips

westward would dip eastward—though at a higher angle than that of the true bedding.

Description: variants of the Lyons formation.—As has been suggested, south of Colorado Springs and north of the Cache la Poudre River, the Lyons beds are not easily recognizable. The southern region may be disposed of briefly. Lateral tracing of the Lyons beyond Colorado Springs is impossible, and certain "coarse deep-red sandstones,"[1] overlying the Fountain sediments west of Pueblo, and "containing a considerable mixture of clay"[2] may be either of Lyons or Lykins time. The same is true of 100 feet of a brick-red sandstone north of Badito; of 30 feet of a massive pinkish-gray sandstone on Grape Creek in the Royal Gorge region; and of certain brick-red material in the Purgatoire Canyon.

The area north of the Cache la Poudre River has been most closely examined by Butters and George; issue is taken with their view with caution, though in this divergence Henderson is again in accord with the writer. Butters' view of this region is as follows. Overlying the typical Fountain material (with its intercalated limestones), he finds a thin series of sandstones and limestones, which he believes to represent a distinct *time-unit* and which he calls "Ingleside"; the deposition of this material transpired, he thinks, between the end of Fountain time and the time of deposition of higher beds supposed to merge southward into material like that of the Lyons.

The writer investigated this region under unfavorable conditions. He is inclined however to follow Henderson in denying validity to the term, "Ingleside," and in considering that, to the south, the lowermost "Ingleside" merges into topmost Fountain and the highest "Ingleside" into lowermost Lyons. The bearing of the discussion on a possible unconformity between Fountain and Lyons is manifest.

Interpretation: the marine hypothesis.—The traditional explanation of the Lyons formation is that it, like the Fountain material, is marine. Fenneman supposes that an eastern sea still encroached upon the land and that waves and currents rolled about the latest

[1] C. E. Gilbert, The Pueblo folio (unpaged).

[2] R. M. Butters, *op. cit.*, p. 75.

Fountain sediments until the orthoclase was decomposed, the muscovite comminuted, and the quartz both comminuted and rounded to a marked degree. The puzzling cross-bedding which now dips eastward at a gentler angle than that of the true bedding he explains more particularly. At certain points of the coast line, he argues, notably at Boulder and Golden, there were elevated east-west arches, separated by bays. Across these bays longshore currents built bars. The cross-bedding represents the originally shoreward dip of this sand-bar.[1]

Interpretation: the writer's desert hypothesis.—Aside from the fact that the marine hypothesis ignores that other large-scale type of cross-bedding which the writer has described, that which under approximate original conditions would dip eastward at a higher angle than the true bedding, many difficulties confront Fenneman's viewpoint. Why do the Lyons sands contain no *coarse* material from the assumed arches? How many bars were there, inasmuch as the cross-bedding is not limited to the Boulder and Golden localities? Are the regular laminae, of which all the beds ultimately consist, consonant with a hypothesis which requires violent waves and currents to comminute and round the quartz grains? Above all, if the trough continued to subside, how could quartz grains, the largest less than 1 mm. in diameter, come to lie in such sharp contact with coarse arkose? And why, if the grains were rolled about under water, did they acquire such films of ferric oxide that the whole formation looks pink to red? Or is the Lyons color entirely secondary?

A very different hypothesis—that the climate grew more arid, that the rivers of Fountain time shrank to nothingness, in short, that desert conditions prevailed when the Lyons sediments were laid down—may not solve all of the difficulties, but it is here advanced as more plausible than the marine hypothesis.

There is certainly no evidence of uplift of the western land at the close of Fountain time. It would accordingly have been lowered by erosion, the rivers would have headed farther back, and they would have brought less and finer materials to the forelands. Winds would thus have had an opportunity to whip about the diminished

[1] N. M. Fenneman, *op. cit.*, pp. 58–60.

Fountain sediments, grinding the feldspar and muscovite to minute fragments and rounding the quartz grains to their unusual uniformity of size and sphericity. Since there would have been a limit to the depth of such wind work, though none to the amount of comminution, the sharp contact of Fountain and Lyons is accounted for reasonably. The very fine irregular cross-bedding on the laminae is such as may be observed on fine, modern sand layers. The large-scale cross-bedding, dipping in two opposite directions at gentle angles, may well have been that of sand dunes, whose topmost layers are truncated as the winds change direction. The uppermost sands, too, are whitest, as if protracted whipping about had removed some of the ferric oxide film. The local conglomerates may have been due to rare, vehement floods from the distant highlands; the boulders are *rounded*, as if they had moved far. Even the sporadic amphibian tracks and the occasional obscure ripple marks are consistent enough with the hypothesis.[1]

There would seem to be, then, a kind of unconformity between the Fountain and Lyons sediments—an unconformity, curiously enough, for which Butters' view of the "Ingleside" would call. But the unconformity would be of an unnamed type, for the record of what happened is not lost. The record takes the form of a geologic palimpsest, as it were—Lyons history being superscribed upon erased Fountain history.

Interpretation: climate and paleogeography.—Lyons climate has already been interpreted as dryer than that of Fountain time. As to relation of land and sea, all that can be predicated is that, as Pennsylvanian time continued, marine or semimarine conditions still prevailed to the north of Colorado, and probably to the east. Western highlands were lowered.

[1] C. E. Vail, "Lithologic Evidence of Climatic Pulsations," *Science*, Vol. XLVI (1917), pp. 91–93, has preceded the writer's point of view by simply stating that the Lyons is eolian, though he has not dealt with its larger problems. In fact, he confines himself to one interesting suggestion. That alternation of light and dark laminae which has been noted he views as the testimony to "climatic pulsations." The "white" laminae he describes as comprising "very well-rounded grains of white quartz, with scattered specks of iron oxide," and the "brown" laminae as being composed of "angular and subangular" grains, with coatings of iron oxide." The brown laminae are then explained as laid down by torrential rains on a desert, the white laminae as being purely eolian. The distinction between the grains of the laminae has perhaps been overemphasized.

THE LYKINS FORMATION

Description: typical Lykins.—The typical Lykins material is both very different from, and much more variable than that of, the Fountain or Lyons series. Yet, except in one important particular, the following section, made at Bear Creek, 3 miles south of Boulder, is representative of the strip from Lyons to some distance south of Colorado Springs.

	Morrison Sandstone, Unconformable on	Feet
k	Sandstone, slabby (2-in. to 4-in. beds), rich brown-red, weathering to red; fine-grained, subhard, ferruginous, somewhat calcareous, slightly argillaceous, breaks in little blocks; rare, comminuted muscovite fragments; ferruginous mud lumps and ripple marks (current type, setting north)	20
j	Shale, fissile, red, sandy	10
i	Sandstone, massive, especially the lower 10 ft.; brown, with green dots, splotches, and lenses, the latter up to 20 ft. long, and passing laterally into sandy shale, almost fissile; no ripple marks observed; mud lumps common. Otherwise, much as in bed *k*	30
h	Shale, red, weathering red, thin bedded to fissile; splotched and lensed with green, varying laterally to shaly sandstone	10
g	Sandstone, almost massive, red—much as in bed *i*, but no mud lumps	60
f	Covered; undoubtedly sandstone and shale, as in beds *g* and *h*, the sandstone predominant, with delicate laminae ($\frac{1}{32}$ in.) on $\frac{1}{2}$-in. beds, the laminae finely cross-bedded	150
e	Sandstone, known as "crinkled" and an important horizon-marker from at least west of Fort Collins to points south of Pueblo; very finely laminated in twisted, broken, and brecciated folds, the average thickness being $\frac{1}{16}$ in., colors alternating red and white; fine grained, hard to superhard, highly calcareous; blocky, shaly sands may be intercalated; upper 6 ft. here limestone, grayish, hard, arenaceous, somewhat brecciated, with calcite crystals in veins	18
d	Sandstone, massive, weathers in blocky fragments, simulating $\frac{1}{8}$-in. to 1-in. beds; red, with less green splotches than in upper beds; variant to *k* type	40
c	Sandstone, massive, red, hard	6
b	Sandstone, much like *k*, but with few mud lumps or ripple marks; green splotches as in bed *d*	34
a	Sandstone, massive, red, weathers in blocky fragments, much as in bed *d*	20
		390

As revealed in this section, the characteristics upon which the interpretation of the Lykins depends are (1) seeming conformity

with the Lyons; (2) fine and uniform grain; (3) vertical alternation of shale and sandstone and lateral passage of the one into the other; (4) presence amid the general red material of green splotches and lenses; (5) occurrence of mud lumps and ripple marks; (6) very fine cross-bedding; (7) origin of the "crinkled" bed, which is not always sandstone, but may carry some thin beds of limsetone, and which may involve varicolored shale lenses, or may even be limestone. Not disclosed in the section is the important fact that the upper few hundred feet of the Lykins often contain gypsum beds, a notable one being 90 feet thick at Red Creek, southwest of Colorado Springs. These gypsum beds all seem to lie above a horizon equivalent to that of certain limestones near the Wyoming line, which carry marine Permo-Carboniferous fossils.

Description: variants of the formation.—South and north of the Cache la Poudre to Colorado Springs strip, conditions are as follows. If the sandstones and shales lying above the Fountain sediments west of Pueblo and Walsenburg (see p. 200) are not of Lyons time, they are probably of Lykins time, since they are unconformable beneath Morrison beds. In the Purgatoire Valley, the Lykins, in all probability, is represented by 800 feet of red sandstones and shales, with gypsum. Any still further eastward extension of the Lykins is discussed under its paleogeography. As to northern Colorado, Butters and the writer (still in accordance with Henderson) are again at variance. Butters believes that the Lykins formation lies directly upon his "Ingleside," and that the writer's "Lyons" is a southern expansion of a thin cross-bedded sandstone which first appears near the Cache la Poudre River and rapidly thickens southward.[1] The writer thinks that Butters' lowest Lykins bed (a shale) merges laterally southward into lower Lyons sands, and that the cross-bedded sandstone, so emphasized by Butters, merges into somewhat higher Lyons sands. The variance hardly bears upon the problems here under discussion, because the northern beds are still marine or semimarine.

Interpretation: marine hypothesis.—Those who regard the Fountain and Lyons sediments as marine assume, without any argument, that in Lykins time the eastern sea deepened.

[1] R. M. Butters, *op. cit.*, p. 76.

Interpretation: the writer's upper-delta hypothesis.—If it is difficult to see why the hypothetically marine sands of the Lyons are pink to red, it is more difficult to picture deepening waters depositing yet redder sediments. It would be daring, indeed, to assume that the present red of these sands and shales was caused by later dehydration of originally gray-green sands; yet, if the western land was now in its last stages of degradation and furnishing primarily red material, why was not the red matter chiefly *mud?* Incidentally, could not invertebrates live in the deepening sea? Marine shale usually preserves traces of life, and, though shale is not predominant in the Lykins, it is nevertheless abundant.

Without directly objecting further to the marine hypothesis, is it not more plausible that in early Lykins time climatic conditions changed, so that the desert slowly became a flood plain or the upper reaches of a delta? There may have been elevation to the west, though the Lykins sediment is as fine grained as the Lyons; there may have been increased rainfall in that region; there may have been solar fluctuations; there may have been an advance of the eastern waters. In any event, the sediments, in many ways, resemble those of the upper stretches of a delta. Already in the lower beds mud lumps begin to appear, and whence arise mud lumps if not from river action? The green splotches and lenses, too, first appear in the lower Lykins. The coloring matter of these green blotches is revealed by analysis as ferrous iron. It would seem unlikely that green was once the prevailing color of sediments now so red. Far more likely it would seem that the blotches are probably due to the reduction of ferric iron, and the most natural reducing agent would be the carbonaceous matter found here and there on the supposed delta. Frequently characteristic of a delta, also, is the change of red sandstone into green shale within the space of a few feet horizontally. Amphibian tracks, too, have been found.

Occasionally, in the time required for the deposition of the Lykins, a sea might have advanced on a delta. Such may be the explanation of the "crinkled" bed, which always occurs near the base of the Lykins. If it were due to a north-south stress in Cretaceous time, as stated by Fenneman[1] and others, strata above and

[1] N. M. Fenneman, *op. cit.*, p. 26.

below might be expected to exhibit signs of disturbance. They do not. If the folding were due to change in volume in underlying beds, "crinkled" strata ought to be fairly common. The Lykins "crinkled" bed seems to stand almost alone. Without asserting that the final word has been said, it may be suggested that limy strata slipped, buckled, and brecciated upon a fairly steep sea slope at a date when the foreland of early Lykins time was submerged.

In upper Lykins time (Triassic?),[1] on the other hand, the climatic pendulum was probably again swinging toward increased aridity, hence the well-known but sporadic and discontinuous deposits of gypsum, and the coarsening of the upper sandstones. Within the last year, also, borings have penetrated salt beds near Eads in southeastern Colorado.

Interpretation: climate and paleogeography.—Climate has been treated of, but it is interesting that what is known of Permo-Carboniferous paleogeography bears out the upper-delta hypothesis. Case, in an elaborate study of Permo-Carboniferous conditions, is rather emphatic in tracing the marine limestone (Wreford) of southern Kansas into the Red Beds (continental) of Oklahoma and thence north to Nebraska and the Black Hills. There would seem, also, to be a relationship between the Cimarron shales of Kansas and the Lykins through the gypsiferous beds at Two Buttes (25 miles west of the Kansas-Colorado line) and in the Purgatoire Valley (see p. 204). Case remarks, finally, that the lower Red Beds of Permo-Carboniferous age are in two areas of deposition, separated (see his Plate IV) by a continuous land mass extending from Mexico indefinitely northward, but at least uninterruptedly to far beyond Colorado.[2] The area of deposition involved in the present problem Case defines as reaching from "north-central Texas to the Black Hills and west to the Front Range of the Rocky Mountains."[3] All this area "can only be considered," he writes, as "great flood plains or deltas."[4]

[1] Whether or not the upper few hundred feet of the Lykins are Triassic, the writer is not prepared to discuss. The evidence consists of a Belodon bone found by Darton in the Purgatoire Valley. See also E. C. Case, "The Permo-Carboniferous Beds of North America," *Car. Inst. Pub. 207*, p. 66.

[2] E. C. Case, *op. cit.*, p. 88. [3] *Ibid.*, p. 71. [4] *Ibid.*, p. 91.

The presence of marine fossils in northern Colorado, up to within roughly the last hundred feet of the Lykins series, would indicate that the expresssion, "continuous land mass," is too sweeping. Case's evidence, however, as to deltaic conditions in Colorado accords with the writer's interpretation of the Lykins sediments.

Conclusions.—It may now be proper to summarize briefly the conclusions reached in this article. They are (1) that the Fountain formation of Colorado is very largely an alluvial fan or braided-river deposit; (2) that the Lyons formation of Colorado is chiefly eolian under desert conditions; (3) that the Lykins formation is chiefly an upper-delta deposit.

ISOSTASY AS A RESULT OF EARTH SHRINKAGE

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In spite of the apparently indisputable evidence that the earth's crust is in almost perfect isostatic adjustment, geologists have been slow to accept the theory of isostasy. The subject received wide interest at the 1921 meeting of the Geological Society of America. At this meeting it developed that the opposition to the theory was directed in part against the common interpretations of some geological phenomena made by the isostasists and also against the lack of interpretations of other geological phenomena which have a bearing on isostasy and appear to be inconsistent with it. Therefore the question arises as to the possibility of explaining these various phenomena in such a way as to satisfy both geological and isostatic requirements.

Those isostasists who claim that mountain ranges have been uplifted by the vertically acting forces of isostasy rather than by the horizontal forces produced by earth shrinkage, have still to explain much in regard to folding and thrust faulting. Bowie believes that these are due to the irregularity of the application of the vertical forces.[1] Irregularities of uplift might produce tilting of surfaces, block faulting, similar folding, and other phenomena which do not indicate a distinct shortening of the crust, but where the cross-section of a range shows that points on the sides of the range have actually moved toward the center so much that there has been shortening of 40 or 50 per cent of the original section, then not vertical forces, but horizontal forces must have been the cause of the structure. It is easy to duplicate experimentally the effects of lateral shortening and to reproduce on a small scale any type of fold found in nature, but it is dynamically impossible to produce overturned folds and thrust faults of large proportions by contrivances which apply

[1] W. Bowie, *Geol. Soc. of America*, Vol. XXXIII (1922), p. 280.

only vertical forces. Hayford's idea that undertow produces folding[1] meets with the same objection, that horizontal surface forces are necessary to produce the shortening which must accompany parallel folding. If it is these vertical forces that produce folding, why is it the peneplain uplifts, which are perhaps the most typical cases of vertical uplift, are generally not accompanied by pronounced folding?

Since there is good geological evidence for shortening of the earth's crust and good geodetic evidence for isostasy, it is fitting that we should examine the possibility that there is no antipathy between the two theories. It has been said that diastrophism due entirely to isostatic forces would soon run down, but if we can consider that earth shrinkage is a cause of perpetuation of the inequalities of the earth's surface, the difficulty is removed. It remains then to explain how the wrinkling of the crust and the various phenomena which geological history tells us have accompanied the changes of the earth's surface could have been produced without the loss of that isostatic adjustment which geodesy leads us to believe has been a basic condition. The following observations appear to be contradictory to the theory of isostasy.

First, the squeezing in of material from the sides in the change from geosynclines to mountain ranges makes it seem likely that the mountain ranges would be a greater burden on the crust than the geosynclines.

Second, the elevation of plateaus from low lying plains appears to suggest that during the process there were important changes in the weighting of the crust with reference to the level of isostatic adjustment.

Thirdly, the development of peneplains and their subsequent uplift gives the impression that the crust is strong enough to resist for long periods without yielding to the forces of isostatic equilibrium.

If diastrophism has been periodic, this also might indicate that the crust was strong enough to withstand great burdens before yielding.

[1] J. F. Hayford, *Science*, New Series, Vol. XIII (1911), pp. 199–208.

MOUNTAIN GROWTH WITHOUT LOSS OF ISOSTATIC ADJUSTMENT

In regard to the possibility of change from geosynclines to mountain ranges without altering the isostatic equilibrium, Bowie offers an explanation which disregards lateral shortening.[1] The gist of this is that while the geosynclines are subsiding, the isogeotherms are depressed beneath them. When subsidence ceases these isogeotherms rise to their former position. The resulting heating of the mass is supposed to be the cause of the mountain uplift by heat expansion. It seems rather doubtful that the slow sinking of a geosyncline would cause a depression of the isogeotherms, but granted that this would actually occur, it must be remembered that subsidence of such geosynclines as the Appalachian was often interrupted and for long epochs the geosyncline was not covered by the sea. If we accept Bowie's idea, we have to account for the lack of mountain building during each of these intervals. The idea therefore does not agree with accurate geological observations.

Considering mountain building as the product of compressive forces, Wood has made the important suggestion that the arching and folding of mountain ranges relieves the burden on the earth's interior[2] and therefore allows the range to stand up without application of extra weight. This explanation does not account for the geodetic observations which show no extra gravity pull for the mountain ranges since the mass of material beneath the range is not changed just because it does not bear down as much on the interior. It is the mass that produces gravity pull. While this may be the cause which initiates the mountain building, something else is necessary to account for the lack of anomalies.

If we examine the history of the geosyncline and range development, we can find a possible explanation. While the geosyncline is sinking, the material in it and beneath it is getting continually more burdened and farther from the surface. If rock material may take on more compact forms as it becomes more compressed,[3] these layers under the geosyncline would be changing into denser

[1] W. Bowie, *Geographical Review*, October, 1922, p. 623.

[2] W. O. Wood, *Bull. Geol. Soc. America*, Vol. XXXIII (1922), p. 312.

[3] T. C. Chamberlin, *Jour. of Geol.*, Vol. XXIX (1921), p. 679.

form. In this process great heat would probably be evolved and would be only in part dissipated toward the surface. The heat might become so great that the temperature for forming molten rock at more moderate pressures might be reached. Presently the geosyncline becomes a zone of such weakness that the compressive forces acting on the crust will produce yielding at that point. There will be first an arching of the formations and thus a relief of the pressure on the interior. This release may make conditions at depth such that the rock will become molten. In the change to the molten condition there is considerable expansion and therefore the earth's crust may be somewhat elevated at this point and still, because of the lightness of the magma, not show positive anomalies at the surface (Fig. 1). Erosion on the mountain

FIG. 1.—Diagrams showing the decrease in density in depth below a mountain range due to the reducing of the overburden by support from the sides and the formation of lava in place.

surface will remove weight and allow a further uplift of the higher portions without increasing the burden or the gravitative pull (Fig. 2).

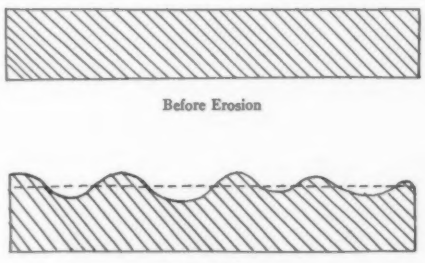

FIG. 2.—Diagrams illustrating how the top of a range may become elevated after erosion has produced irregularities. The total weight on the base is the same in each case.

THE ISOSTATIC DEVELOPMENT OF PLATEAUS

As to the development of plateaus there has been no attempt on the part of the isostasists to offer an explanation. Plateaus seem to be connected with the formation of great magmatic bodies beneath the surface. If these bodies are formed in place, the expansion could be great enough to cause the uplift without increasing the gravity. A broad arching of the crust such as occurs under plateaus might relieve the pressure sufficiently to cause a zone that was already heated to become molten. As the magma body cooled the plateau might be expected to sink, unless the erosion of the surface was equal in rate to the contraction produced by the cooling of the magmas. Plateaus are not known to have existed through long ages and are probably only temporary features.

EXPLANATION OF PENEPLAINS AND THEIR REJUVENATION

Peneplanation of mountain ranges and the subsequent uplift of these peneplains has seemed to many to be an insurmountable argument against isostasy. Even Barrell considered that peneplanation must indicate a successful resistance of the earth's crust to isostatic forces.[1] If the base of a range remains at a more or less constant elevation throughout the process of peneplanation and the range is losing weight continually by erosion, it might seem certain that it would be getting out of isostatic adjustment during the process. Bowie's answer to this objection is that a range is being constantly elevated by isostatic adjustment but not as fast as it is being eroded, because as the isostatic flow at depth continues to add material to the base of the range, it adds less material than is being substracted by erosion, because the material at the base of the column is more dense than that at the surface, and thus less has to be added to keep the column in equilibrium (Fig. 3). It seems doubtful whether this factor would be sufficient to produce peneplanation without the transference of tremendous amounts of material, probably tens of miles, because while the mountain column might be getting lower due to the adding of less material at depth, it would be getting higher due to the expansion

[1] Joseph Barrell, *Jour. of Geol.*, Vol. XXII, p. 30.

of the material produced by the relief of pressure in the erosion, and this expansion would offset much of the lowering. Neglecting the expansion factor and considering the depth of compensation as 67 miles, a difference of density of 6 per cent would necessitate erosion of some 50 miles of material to reduce to sea-level a mountain range 3 miles high.

Let us see what else could produce peneplanation. If a mountain range is being maintained in spite of erosion because of having the curvature of an arch, once this arch is broken or truncated by erosion the lateral forces will no longer be competent to support the

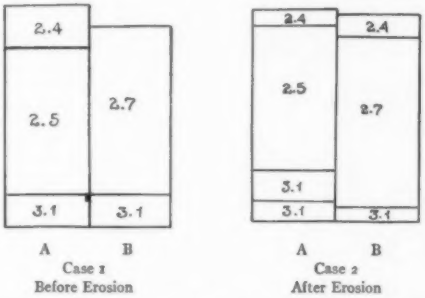

FIG. 3.—Diagrams illustrating Bowie's idea of the cause of peneplains. *A*, Mountain column; *B*, Piedmont plain column. In each case *A* and *B* are balanced in weight.

range and a peneplain may result by cessation of uplift. If the magmatic body beneath a mountain range cools or works its way to the surface, the density conditions will change and the region can no longer remain in equilibrium as a mountain range. If the lateral support which is maintaining a mountain range can be transferred to other zones of weakness, the mountain range will no longer be a rising column and erosion can soon reduce it. Thus there are several ways in which peneplains can be produced without loss of isostatic adjustment. It seems only natural that a region which is held above its surroundings by some abnormal means should be reduced to its previous level by changing conditions.

There remains to be explained the renewed uplifts of peneplains. Supposing that the peneplain was reduced by the removal of the

lateral support of the range, it is not inconceivable that the conditions would change again sufficiently to renew the support. A recurrence of vulcanism beneath the range would produce a new uplift by the expansion of the underlying material.

A CHALLENGE OF THE BASIS OF PERIODIC DIASTROPHISM

If the history of the earth actually shows periodic diastrophism and this periodicity is due to a long accumulation of strains followed by readjustment, then isostasy has not always been operative. On the other hand, if the apparent periodicity of diastrophism is due to periodic shrinkage of the interior, the isostatic condition may not be affected. However, there is perhaps some reason to question the whole idea of periodicity.

Continuity of diastrophism in the past does not mean that there was diastrophism of all parts of the crust at all times, but that the earth's crust was taking up shrinkage of the earth's interior by being constantly folded or faulted in one or several places according to the concentration of the shortening. Therefore, periodic folding in one region does not prove that diastrophism was universally periodic. Folding very likely occurred in the weakest zones of the crust. After a certain amount of shortening a zone may become more rigid and allow the folding to be transferred elsewhere.

Wide marine invasions of the lower parts of the continents are thought to indicate periods of quiet unaccompanied by diastrophism. If the shortening of the crust is temporarily transferred from the continents to the ocean basins, the folding under these basins will raise the sea-level and cause an inundation of the lower parts of the continents which will produce the epi-continental seas without a cessation of diastrophic movements.

If diastrophism has been continuous in the past, would its records of times of disturbance be equally continuous? We have a vast store of illustrations of past diastrophic movements, but in very few instances are we able to give the exact time at which the orogenic movement was initiated and the time at which it terminated. Much too often a clue as to the time of origin of one small section of a great mountain system has to be taken as the time of origin

of the entire system. Since some fairly recent mountains show evidence of several deformations we would perhaps not be wrong in concluding that mountain ranges which originated far in the past have been frequently rejuvenated. The records of times of such rejuvenations are rarely found. Added to those ranges which took up the shortening of the crust on the continents there were probably many ranges on the sea bottom which could have left no time record. Therefore, for these reasons, if we consider that the upper rectangle in Figure 4 represents continuous diastrophism, it is likely that incomplete geological records would show something of the order of the lower diagram (Fig. 4).

If we consider that individual orogenic disturbances on the average continue from one-third to one-half of a period, then the

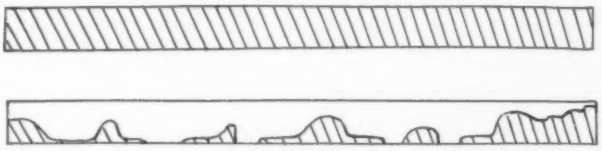

FIG. 4.—Diagrams illustrating the replacing of a complete series of deformations (above) by a fragmentary series of records (below) because of incomplete geological data.

records of the times of deformation, which have been compiled, are surprising, not in that they show infrequent deformations, but that they show an almost uninterrupted series of orogenic movements in one part of the world or another. They scarcely illustrate a contemporaneous origin of two large mountain systems. The most complete records, which are of the Cenozoic disturbances, show an almost equal distribution of diastrophism in the different divisions of the era. Only where the records have been much effaced farther back in the time scale are there indications which point toward periodicity. Even in the Paleozoic, diastrophic movements do not appear to come especially at the end of periods. In an article compiled by R. T. Chamberlin,[1] the times of Paleozoic deformation are given. A critical examination of the evidence of

[1] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXII (1914), p. 315.

the exact times of these disturbances shows that out of 54 only 9 can be said with any certainty to have occurred at or very near the division between the periods, and so far as can be told from the rest they may have occurred well within one of two or even three periods. Therefore the numerous disturbances may be taken as well to indicate a continuous series of orogenic movements as an intermittent series.

Therefore the conception of periodic diastrophism should be critically re-examined and the evidence sifted with care before it can be used as an argument against continuous isostatic adjustment.

THE DEVONIAN LIMESTONE AT ST. GEORGE, QUEBEC

THOMAS H. CLARK
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An area of fossiliferous rocks which has received scant attention in the past is that of the Devonian limestone at St. George, Quebec, on the Chaudière River. In 1863, Logan[1] devoted a page or two to the limestone and its fauna, and again in 1888 Ells[2] referred to them very briefly. In the scramble to attack problems in more alluring areas geologists and paleontologists alike have passed these outcrops by. Few geologists enter the territory between the St. Lawrence River and the Maine boundary, unless it be for the purpose of examining the asbestos deposits at Thetford, or of exploring among the crystallines which outcrop along the International border. Paleontologists find little to attract them south of the fossiliferous Lévis shales along the St. Lawrence itself, and a glance at Ells's map of the country to the south shows the symbols denoting fossiliferous localities to be few and very far between. Recently B. R. MacKay[3] has published an account of these rocks in a memoir primarily concerned with the genesis and distribution of the placer gold of the region, but the stratigraphy and structure have been worked out as carefully as that difficult terrane permits. The Devonian outcrops in question have been restudied and the fauna reported on by Kindle. The writer's collection of fossils from this limestone was made during the last two years, and seems to shed some light upon the larger problems connected with the Middle Devonian.

[1] Sir William Logan, *Geology of Canada* (1863), p. 428.

[2] R. W. Ells, "Second Report on the Geology of a Portion of the Province of Quebec," *Geol. Surv. Can., Ann. Rept.* (1887), Part K, pp. 9–11K (1888).

[3] B. R. MacKay, "The Beauceville Map-Area, Quebec," *Can. Geol. Surv., Memoir 127* (1921), pp. 31–33.

The limestone is dark gray, almost black; and is crowded with fossils wherever it outcrops. It is rarely crystalline, but, upon weathering, breaks down into a rubbly mass with little dependence upon the inclosed fossils. Good opportunities for collecting are therefore rather unusual, except on the weathered surfaces. Whole specimens of brachiopods were not collected as such at the outcrops, but were worked out in the laboratory. The corals, on account of their much greater size, could be collected whole, the limestone disintegrating around them. A day's search failed to reveal any trilobites, although they have been reported before. The brachiopods were almost exclusively of two species; what was the relative abundance of the species collected by Logan and by Ells is not stated in their reports. There is no doubt, however, about the Onondaga age of the fauna. This will be shown by the following list and descriptions of fossils recently collected by the writer.

COELENTERATA

Favosites basalticus (Goldfuss)[1]

One of the most abundant species present. The specimens are in every way characteristic. Although Ami is reported as having recognized *F. gothlandicus* from this locality, not a single specimen in our collection can be placed in that species. Every individual examined (a score or so) lacks spines within the corallites, but there are many squamulae between the tabulae. The presence of spines has often been considered an evidence of the Silurian age of a Favosites, whereas squamulae are characteristic of Devonian species.

Diphyphyllum arundinaceum (Billings)[2]

One of the most striking characteristics of our specimens is the wide spacing of the strong simple tabulae. There are from six to eight of these in each 10 mm. The corallites seldom reach 10 mm. in diameter. More often they are less than 8 mm. The largest specimen is 21 cm. from "root" to the outermost calyx.

[1] L. M. Lambe, *Geol. Surv. Can., Contr., to Paleon.*, Vol. IV (1899), Part I, p. 8. Full lists of references are not given. Only those most easily accessible to students are included.

[2] Lambe, *ibid.*, Part II, p. 162; H. A. Nicholson, *Paleontology of Ontario* (1874), p. 34.

Cyathophyllum sp.

Great numbers of corals belonging to this genus occur at this locality, but none of them shows specific characteristics. It is probable that two, or even more, species are represented in the collection.

Cystiphyllum vesiculosum (Goldfuss)[1]

One specimen only of this species was collected. It is typical in all respects, except that it is not complete enough to show the calyx.

Zaphrentis Rafinesque and Clifford sensu stricto[2]

One specimen of a Zaphrentid coral with a well-developed fossula, and with septa (not carinated) extending fully to the center of the visceral chamber, is present in the collection. It consists of little more than a cross-section, so that nothing can be said of its external form. In the collection made by Logan and examined by Billings, an unidentified Zaphrentis was listed.

Amplexus cf. hamiltoniae Hall.

Two small specimens are placed provisionally in this species. In both, the external ornamentation is preserved exceptionally well, but almost all traces of internal structure have been obliterated by the crystallization of the interior. Septa may be seen within one specimen, closely crowded, and produced about a quarter of the distance from the outer wall to the center, but whether these represent the original length, or only such parts as have escaped crystallization is uncertain.

Syringopora tabulata (Milne-Edwards and Haime)[3]

This is one of the largest corals found at St. George, rivaling *Favosites basalticus* in size. Some of the specimens, incomplete, weigh as much as 15 pounds, and are 40 cm. on their greatest diameter. Ami has identified *S. hisingeri* from this locality, but none of our forms belongs to that species. In all of our specimens, the corallites are never separated by spaces greater than their own diameter, and the connecting tubes are disposed at uniform levels.

Stromatopora Goldfuss (emend. Nicholson)[4]

[1] M. Edwards and Haime, "Mon. Brit. Corals," *Paleon. Soc. London* (1850), p. 243; Lambe, *op. cit.*, Part II, p. 192.

[2] M. O'Connell, "Revision of the Genus Zaphrentis," *Ann. of the New York Acad. Sci.*, Vol. XXIII (1914), pp. 188–89.

[3] C. Rominger, *Geol. Surv. Mich.*, Vol. III (1876), Part II, p. 84.

[4] H. A. Nicholson, "Mon. Brit. Stromatoporoids, *Paleon. Soc. London* (1886), p. 91.

Our specimens are all of a gently undulating, flattened form, but much of the structure has been destroyed by weathering. This condition is not confined to the surface, for much of the internal structure of the fossil is now indistinct. Beyond a rugosity developed somewhat concentrically within a slightly upturned margin, there are no surface markings of distinctive value. The best natural section of the skeleton shows very fine corrugations spaced $4\frac{1}{2}$ per millimeter. These appear upon a polished surface as lines of black dots crossing the white calcite. It may be that these dots represent the junction of radial pillars with the laminae, but neither pillars nor laminae have been preserved. The same structure is expressed on weathered edges by extremely fine ridges. Under these circumstances, specific identification is impossible, and even generic determination is largely a matter of conjecture. Our specimens are from 10 to 24 mm. thick, and the largest fragment is 34 cm. across. This was broken from a whole specimen which was more than 2 feet across.

BRYOZOA

Three or four species occur in the collection, but I have not attempted their identification. They are for the most part Fenestellids.

BRACHIOPODA

Stropheodonta sp.

The interior of a pedicle valve of a species belonging to this genus is present in our collection. It has no characteristics of specific import.

Atrypa reticularis (Linné)

Abundant. Our specimens vary in form from those in which the valves are equally convex to those in which the pedicle valve is almost flat. They are all rather small, seldom attaining a width or a length of 20 cm.

Spirifer lucasensis Stauffer[1]

Much more abundant than *Atrypa reticularis*. Our specimens are identical with those from Ohio, save that in some the hinge line is a little less than the greatest width of the valves. Inasmuch

[1] C. R. Stauffer, *Geol. Surv. Ohio., Bull. 10* (1909) fourth series, pp. 188–89, Pl. 16, Figs. 1–5.

as our specimens show all gradations between such a form and another in which the hinge line exceeds the greatest width of the valves, I have assumed that this variation is of minor importance. The significance of the association of this species, which in Ohio occurs in beds of Hamilton age, with true Onondaga corals, is discussed below. This is probably the species identified by Billings, Ami, and Kindle as *S. gregarius* Hall. Stauffer has suggested that two of Hall's figured specimens of that species[1] may belong to *S. lucasensis*.

GASTEROPODA

Igoceras cf. conicum (Hall)
Igoceras cf. plicatum (Conrad)

Fragmentary representatives of this genus were collected at St. George, and tentatively assigned to the species suggested above.

THE AGE OF THE LIMESTONE

There is an apparent contradiction in the evidence presented by the fossils. All of the corals definitely identified are typical Onondaga species, and as they far outnumber, both in species and in number of individuals, the representatives of other phyla, we may assume for them a higher diagnostic value than for the other fossils. In fact, there is but one other fossil with any diagnostic value in our collection—*Spirifer lucasensis*, which has previously been reported from the Delaware formation (the equivalent of the Hamilton and Marcellus beds) of Ohio. The Columbus limestone, which underlies the Delaware formation, is rich in corals, and is the western equivalent of the Onondaga. Corals do occur in the Delaware, but they are not characteristic of that formation. Since the Delaware postdated the Onondaga of Quebec, *S. lucasensis* is evidence of a faunal migration westward near the end of Onondaga time. At about this time the St. Lawrence channel was permanently closed, and a retreat of the waters from the maritime provinces westward ensued. Such a retreat could not promote a continuance of the clear waters which the Onondaga fauna predicate; in fact, in the sediments immediately succeeding this event we have

[1] James Hall, *Palæontology of New York*, Vol. IV, Pt. I, Pl. 28, Figs. 9–10.

evidence of muddy waters, in which the coral fauna was extinguished. Other forms, more hardy, or less susceptible to slight changes in their habitat, could migrate with the retreating sea. In Indiana, Ohio, and Michigan clear-water conditions prevailed throughout the Middle Devonian, so that the presence there of a somewhat restricted coral fauna above the Onondaga is not surprising. It is supposed that *S. lucasensis* took part in this westward migration, reaching the northwestern part of the Ohio Basin in Hamilton time.

EXTENT OF THE ONONDAGA SEA

The association of typical Onondaga corals with a brachiopod found in the Hamilton of Ohio suggests one minor readjustment of the paleogeographic maps of the continent in Onondaga time. *Spirifer lucasensis*, originating in the East, migrated to Ohio by some path no trace of which has to date been reported. In spite of the intensive search for fossils in the Devonian rocks of New York State, this Spirifer has not been found. It seems probable, then, that this fossil did not follow along the line indicated by the present outcrops of Onondaga in New York from the Helderbergs westward. A glance at Schuchert's paleogeographic map for the late Onondaga, or at the map for Onondaga time in Grabau's *Text-Book of Geology*, shows a land area bordered approximately by Lake Huron on the west, the Hudson-Champlain line on the east, the present Onondaga outcrops on the south, and unlimited to the north. Inasmuch as all of this area south of the forty-fifth parallel was certainly covered by Ordovician sediments, which probably extended as far north as Lake Temiskaming, it does not seem improper to suppose that the Onondaga sea also covered much of it. If the strand line be drawn from Montreal westward along the forty-fifth parallel to Lake Huron, we shall have a much more probable distribution of land and sea than the maps show. Coral faunas require a wide, open seas, rather than narrow channels. It is a question how close to an outcrop of Onondaga limestone one can draw the strand line. In this case, the cartographer may be allowed more latitude than when dealing with detrital rocks. Such a boundary as suggested would remove from the present maps the

objection that the long line of Onondaga outcrops in New York borders too closely a land mass, and would provide the clearer, off-shore sea which the fauna seems to require. And, moreover, it would provide a pathway, all traces of which are now obliterated, for the migration of *Spirifer lucasensis*.

A paleogeographic map of North America during Onondaga time is submitted with this report. It will be seen that the distribution of lands and seas is shown on a much more simple plan

FIG. 1.—Paleogeographic map of North America during Onondaga time. Shaded areas represent seas.

than in most maps representing the geography during this period. Simplicity, when compatible with the facts, is desirable in our necessarily crude reconstructions of the continent. In this respect the paleogeographic maps in Grabau's *Text-Book of Geology* are inferior to their predecessors, for their complicated shore lines are apt to give students the idea that our knowledge of paleogeography has reached that stage of perfection in which shore lines can be plotted accurately and in detail. Such is not the case, nor is it ever likely to be; so that for both scientific and pedagogical

reasons we should use, in general, easy-flowing lines such as those which characterize Schuchert's paleogeographic maps.

The St. Lawrence Channel was open for the greater part if not all of Onondaga time. The northern shore line from Montreal west to Lake Huron is drawn in accordance with the conclusions reached above. In Dunbar's map,[1] this shore line is placed much farther south, probably through inadvertence, there being no reason for showing a land area on the site of the long east and west outcrop in New York. The irregularities in the shore line around the Great Lakes and to the south[2] are omitted, for some seem not to be well founded, and none is essential. The western shore line of southern Appalachia is removed somewhat eastward, in order not to embarrass the coral faunas of western Tennessee and Kentucky.

The "New Jersey Strait" is not represented on the present map, but instead there is a wide sea-way traversing southern and central New England. In general, a wide strait is preferable to a narrow one, and, in particular, it seems unlikely that there was a sea-way across New Jersey, on account of the great thicknesses of delta deposits which accumulated there only a few epochs later. If there is an error in the position of this New England Channel, it is probably that it lies too far south.

From the Onondaga onward, Appalachia began to rise and to extend northward. By the close of Onondaga time, it had effected a junction with the island across the New England Channel, thereby closing it. It has been supposed that the St. Lawrence Channel was closed at the end of the Onondaga, and this is probably correct. The rising Appalachia was later to shed the enormous amount of sediment comprised in the Upper Devonian deltas of the northern Appalachian region. With the St. Lawrence and the New England channels closed, subsequent invasions of European faunas must be explained as having come by way of the Arctic rather than by the Atlantic Ocean.

The Cincinnati dome is not represented as an island upon this map, because it was probably covered much, if not all, of the time

[1] Carl O. Dunbar, "Stratigraphy and Correlation of the Devonian of Western Tennessee," *Geol. Surv. Tenn., Bull. 21* (1919), Fig. 3B.

[2] See Stauffer, *op. cit.*, Pl. 14.

by the Onondaga sea, for as Miller states[1] "in the succeeding Middle and Upper Devonian submergence, sediments were laid down unobstructedly and with great horizontality across the Arch," though this conclusion has been questioned.

The shore line in western United States is copied from Schuchert's map. There is some doubt as to the Onondaga age of the outcrops on which this shore line is based, and there seems to be no good reason for placing the Onondaga shore line so far west of the present strand, but those are subjects with which this paper is not primarily concerned.

[1] A. M. Miller, "The Geology of Kentucky," *Department of Geology and Forestry of the State of Kentucky, Bull. 2* (1919), fifth series, p. 77.

DID CRATER LAKE, OREGON, ORIGINATE BY A VOLCANIC SUBSIDENCE OR AN EXPLOSIVE ERUPTION?

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The great volcanic eruption of 1912 at Katmai, Alaska,[1] has again called the attention of geologists to Crater Lake, Oregon, with the suggestion of a similar explosive origin of the great depression containing that lake, which depression had previously been ascribed by the present writer[2] to subsidence.

Crater Lake is in a deep abrupt basin about 5 miles in diameter and 4,000 feet deep in the plateau-shaped summit of the Cascade Range.

Crater Lake is completely encircled by a very bold rim which rises to approximately 2,000 feet around the lake, which is about 2,000 feet deep. The rim has a very steep slope inside toward the lake but a gentle slope outside to the summit-plateau on which Mount Mazama was built up by many successively overlapping lava flows and sheets of ejected volcanic fragments, all erupted from practically the same volcanic orifice.

Nearly all this rim, however, was built up by eruptions of andesite before the eruptions of dacite began.

Much dacite-pumice formed a partial top-rim of Crater Lake, but the succeeding dacite flow from the summit of Mount Mazama finally broke from the surface of the lava tunnel at Rugged Crest and overflowed down the inside of the rim into the head of Cleetwood Cove of Crater Lake as Mount Mazama sank away into engulfment, leaving the outer slope of the rim with its fresh flow of dacite and the glaciated rim with its glacial striae and moraines, as shown on the map, Figure 13, *Geological History of Crater Lake National*

[1] Robert Fiske Griggs, *The Valley of Ten Thousand Smokes.* The National Geographical Society, 1922.

[2] "Geology of Crater Lake National Park 1902," *U.S. Geol. Survey Professional Paper No. 3.* Also *Geological History of Crater Lake National Park.* Dept. of Interior, 1912.

Park, 1912, entirely uncovered by any material that could have been blown out from Mount Mazama to make the great depression for Crater Lake if Mount Mazama was *blown away à la Katmai* and *not engulfed*.

The most striking evidence of the engulfment of Mount Mazama is afforded by the inflowing stream of dacite, Fig. 1, from the notch produced by the cave-in at Rugged Crest down the inner

FIG. 1.—The inflow of dacite at Cleetwood Cove of Crater Lake

slope of the rim to Cleetwood Cove of Crater Lake. The view shows the whole length of the inflow from the notch of Rugged Crest to the shore of the lake, and it appears that Mount Mazama sank away about the time the final flow of dacite occurred, for the dacite beneath the crust at Rugged Crest was still soft enough to flow and to cause the crust to break and cave in. The broad flow of dacite from Rugged Crest northeast down the outer slope of Mount Mazama is shown in Figure 1, also the short flow inward to the lake.

AN IMPROVED RECORDING MICROMETER FOR ROCK ANALYSIS

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Numerous methods have been devised for the quantitative estimation of the mineral composition of rocks by measurement of the minerals appearing in thin sections. These have been described in detail elsewhere,[1] and it is not the writer's purpose to consider their relative merits at length. All these methods involve the measurement of areas either directly or by weighing dissected rock patterns, or of intercepts of the several minerals along certain selected lines. In any case, the number of measurements must be large in order to overcome the errors due to variation in grain size and irregularity of distribution of the minerals, and the process by any one of the methods is a somewhat laborious one. Among the several methods, that of Rosiwal seems to combine the requisites of simplicity and relative accuracy. This method has been the subject of careful examination by Johannsen and Stephenson[2] from the empirical standpoint, and by Lincoln and Rietz[3] from the theoretical as well as the experimental point of view. The work of these investigators proves adequately the validity of the method, and that of Lincoln and Rietz is valuable particularly in offering the means of defining somewhat accurately the requisite number of measurements for a given degree of precision in results obtained under various conditions.

[1] A. Johannsen, *Manual of Petrographic Methods* (New York, 1914), pp. 290–92, and "A Planimeter Method for the Determination of the Percentage Compositions of Rocks," *Jour. Geol.*, Vol. XXVII (1919), pp. 276–85; A. Holmes, *Petrographic Methods and Calculations* (London, 1921), pp. 310–22; J. Hirschwald, *Handbuch der bautechnischen Gesteinsprüfung* (Berlin, 1912), pp. 146–47, 163–72; A. Rosiwal, "Über geometrische Gesteinsanalysen," *Verh. der k. k. geolog. Reichanstalt* (Wien, 1898), No. 5.

[2] A. Johannsen and E. A. Stephenson, "The Rosiwal Method for Minerals," *Jour. Geol.*, Vol. XXVII (1919), pp. 212–20.

[3] F. C. Lincoln and H. L. Rietz, "The Determination of the Relative Volumes of the Components of Rocks by Mensuration Methods," *Econ. Geol.*, Vol. VIII, pp. 120–39.

Their work, as well as that of other students, indicates the need of large numbers of measurements to insure results of requisite accuracy, and the usefulness and popularity of the Rosiwal method depends upon the simplification and standardization of the mechanical and numerical operations involved. This was recognized in 1916 by Shand,[1] who described a recording micrometer which served both to make the measurements and to add the resulting figures. This instrument, which can be attached to the stage of any petrographic microscope, saves the large amount of labor and eye strain previously involved in the adding of the data as well as in the concurrent recording and observation. It has, however, one important defect, as Shand himself recognized,[2] in that it can be used to measure but two constituents at a time (any one mineral and the remainder of the rock). In case more minerals are to be estimated, it is necessary to repeat the operation.

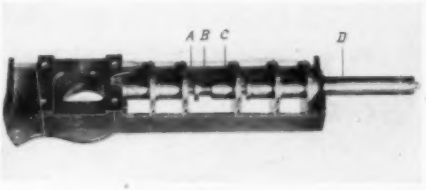

FIG. 1.—Improved recording micrometer. *A* is a square rod, *B* is a screw with an axial square hole which fits *A*, *C* is a nut and dial fitting the threads of *B*, *D* is the housing of a tension spring which pulls the slide carriage toward the right. Parts slightly separated to show relations of *A*, *B*, and *C*. Normally the spring keeps these together.

Having occasion recently to make a number of such estimates of rock composition, and needing some sort of device to do the work, the writer found it possible to overcome the limitation of the Shand micrometer by the mechanical device shown in Figure 1. This was constructed by Mr. Stanley Price, mechanician, of the State University of Iowa, according to the writer's specifications. It consists essentially of a single sledge which is actuated by a series of screws and nuts arranged in a string on a square rod at one side. The screws are free to slide but are prevented from turning by the square hole by which each is fitted to the square rod. The nuts consist of the threaded sleeve and a graduated dial by which their motion is recorded. The position of the sledge, which is held against

[1] S. J. Shand, "A Recording Micrometer for Geometrical Rock Analysis," *Jour. Geol.*, Vol. XXIV (1916), pp. 394–404. [2] *Ibid.*, p. 399.

the string of screw-nut pairs by a spring, is determined by the total length of the string. The latter is adjustable by rotating any one of the several nuts. Thus, the sledge carrying the rock section may be driven across the field of view by turning the appropriate dial in crossing the part of the section occupied by each of the several minerals. Thus, as many minerals as desired may be measured, recorded, and the results added, in one operation. The instrument, as constructed for the writer, carries five dials, but any number may be added by increasing the length of the machine. In order to avoid the necessity of having an exceptionally strong backlash spring, it is found desirable to traverse the sections in the same direction by increasing the length of the string of screw-nut pairs. With this precaution, which is good practice with any instrument of this sort, the micrometer as shown gives excellent results. The Bausch and Lomb Optical Company has the necessary data for constructing duplicates of this instrument and will furnish estimates on request. The following measurements of the minerals of a thin section of granite will serve as an example of its performance.

TABLE I

INSTRUMENT READINGS—TRIAL I

Quartz	Feldspar (Chiefly Orthoclase)	Biotite	Apatite
527	291	∞	68
466	592	∞	113
283	1,207	54	∞
387	1,221	∞	∞
718	853	136	∞
1,152	605	158	72
418	954	530	54
795	873	240	∞
629	1,255	47	∞
645	1,088	103	∞
593	857	95	∞
770	760	15	∞
747	757	∞	28
405	732	13	145
174	605	∞	∞
8,709 (37.55%)	12,650 (54.40%)	1,391 (5.99%)	480 (2.06%)
			1,391
			12,650
			8,709
Total.....	.....	.....	23,230

Each trial consists of fifteen transepts of the section at intervals of one millimeter, the second series starting one-half millimeter nearer the edge of the section so as to occupy positions staggered with those of the first series. Each transept crosses an average of about ten mineral grains. The measurements, readings, and recording of totals for the transepts were completed for each trial in about thirty-five minutes.

TABLE II

INSTRUMENT READINGS—TRIAL II

Quartz	Feldspar (Chiefly Orthoclase)	Biotite	Apatite
483	455	oo	168
265	940	66	oo
423	1,162	oo	oo
416	1,191	oo	oo
1,023	703	57	oo
758	582	279	249
504	815	476	58
862	1,025	54	oo
518	1,287	122	oo
700	1,096	93	oo
675	649	124	oo
824	767	28	oo
726	662	oo	61
301	785	13	80
45	475	oo	oo
8,523 (37.00%)	12,594 (54.55%)	1,312 (5.69%)	616 (2.67%)
			1,312
			12,594
			8,523
Total.....	.....	.....	23,045

It will be seen that there is rather good agreement in the results for the three more abundant constituents but less satisfactory agreement in the percentages for the apatite. Considering the scarcity and irregular distribution of the mineral, this result is not surprising and is only to be improved by a much larger series of measurements.

Although the writer has never used an instrument of the Shand type, he is confident that the instrument here described can be handled with equal facility in any kind of measuring operation and has the important additional advantage of permitting simultaneous estimation of any number of constituents with the resulting economy

of time. In case one wishes to identify a mineral grain between crossed nicols, the instrument can be rotated through more than 270 degrees of the motion of the stage (Fig. 2). Certain improvements occur to the writer which might be followed by anyone wishing to duplicate the instrument. The one constructed for the writer weighs about twenty-one ounces. The use of aluminum-zinc alloy instead of brass for certain parts and attention to details of design would probably result in reducing this weight by nearly one-half. The substitution of celluloid dials and black graduations for the brass dials on the instrument shown would greatly increase the ease of reading the instrument. In the present instrument, whole turns are read by counting threads exposed or by measuring with a scale; a thin scale could easily be added to each screw by means of which these could be read at once. The pitch of the screws ideally should be 1 millimeter and the graduations of the dial .01, though in practice the graduations of the model, which are .008 mm., are equally satisfactory, since computations are wholly relative.

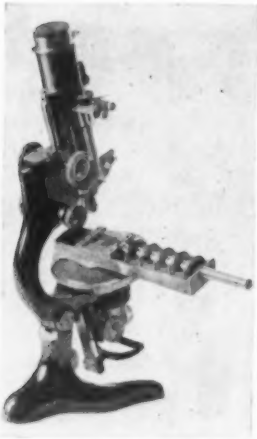

FIG. 2.—Micrometer mounted on stage of Leitz petrographical microscope.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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VII

VISCOSITY, SIZE OF CRYSTALS, SPEED OF CRYSTALLIZATION, FORMATION OF GLASS, INFLUENCE OF TIME, UNDERCOOLING (OR SUPERSATURATION), AND EQUILIBRIUM OF MIX-CRYSTALS BETWEEN THE SOLID AND LIQUID PHASE, ETC.

We have only empirical methods for the measurement of *viscosity*, e.g., submersion of a ball of a certain weight for a certain period, resistance to stirring, the length of an out-pulled thread, etc.

At one and the same temperature the various silicate melts (at one atmosphere pressure) are characterized by greatly varying viscosity.[1] To be convinced of this, laboratory experiments are not needed, as we only need to refer to the well-known phenomena seen in the large, molten masses at smelting-plants, glassworks, etc. As I have had a rather considerable experience in this matter for the judgment of the temperature supported by measurements with Le Chatelier's and optical pyrometers, I shall give a review of the degree of viscosity of various silicate melts, mainly metallurgical slags and several glasses.

At first, according to an old experience that is also confirmed by laboratory measurements, we notice that the viscosity decreases with increasing temperature, though in a highly varying degree for the various melts.

[1] Cf. especially E. Greiner, "Ueber die Abhängigkeit der Viscosität in Silikatschmelzen von ihrer chemischen Zusammensetzung," Ing Diss., Jena, 1907 (with references to the previous literature). Further the chapter "Ueber die Beziehung zwischen Viskosität, Krystallizationszeit und Krystalgrösse" and "Weshalb ist das Glas eine feste Lösung?" in *Silikatschmelzlösungen* 1904, I, 156–69, besides earlier treatises by J. H. L. Vogt, especially one in *Zeitschrift für praktische Geologie* (1893), p. 275.

Extremely thin.—Basic slags with predominant MnO, as

SiO_2	MnO	FeO	Al_2O_3,	CaO,	etc.
30–45	30–40	5–25	0–4		

With the exception of certain silicate melts rich in PbO, melts rich in MnO are the thinnest silicate melts I know, and they are also extremely thin at the temperatures immediately above or at the beginning of crystallization (of manganese-fayalite or rhodonite). In the common silicate slags with as much MnO as 10–15 per cent, MnO causes a noticeable increase in thinness.

Exceedingly thin.—Basic slags with predominant FeO, as

SiO_2	FeO	CaO,	MgO,	Al_2O_3	etc.
25–30	60–70		3–10		

These are also very thin, even when cooled to the beginning of the crystallization (of fayalite).

In slags with predominant FeO, the viscosity is somewhat greater when the percentage of SiO_2 rises to 40–45 per cent, and the viscosity is considerably increased when the percentage of SiO_2 rises above 55 per cent.

In the common CaO+MgO slags with some Al_2O_3, FeO causes an increase of thinness, hardly however to the extent shown by those with MnO.

Very thin at about 1,400°.—Middle basic melts with approximately equal proportion of CaO and MgO,

SiO_2	CaO	MgO	Al_2O_3	MnO+FeO
30–40	30–40	20–30	0–5	0–4
40–45	30–40	10–20	2–7	0–4
40–45	15–30	20–30	2–7	0–4

The thinness seems to increase somewhat when CaO is replaced in part by MgO. This may not be maintained with absolute certainty, however.

In an intermediate mixture of CaO and MgO, the viscosity increases with increase of SiO_2, when SiO_2 amounts to more than 50 per cent.

Thin at 1400°.—Silicate melts with

SiO_2	CaO	MgO	Al_2O_3	FeO, Mno
50	25–30	15–20	2–5	1–3

Further, melted diopside

SiO_2	CaO	MgO
55	26	19

But when SiO_2 amounts to 60–65 per cent, as

SiO_2	CaO	MgO	Al_2O_3
60–65	20–25	about 10	about 5

the molten masses are *rather* viscous. And with still more SiO_2 and decreasing CaO+MgO, the degree of viscosity is *considerably increased* so that with about 75–80 per cent SiO_2, even at temperatures as high as 1500°–1600°, a very considerable viscosity is involved. As to pure SiO_2, see below.

Al^3O^2-bearing silicate melts.—A few per cent of Al_2O_3 seem to have no traceable influence on the viscosity of basic silicate melts with predominant CaO, MgO, FeO, etc. Basic slags with somewhat higher percentages of Al_2O_3, as

SiO_2	Al_2O_3	CaO	MgO
30–35	15–25	30–40	5–10

wherein melilite-gehlenite (with spinell, etc.) crystallizes to a considerable extent, seem throughout to be rather thin at a temperature about 1400°. (As to anorthite see below.)

If we pass to somewhat more *acid* slags, we find that Al_2O_3 induces considerable viscosity. Thus slags, as e.g., the Mansfelder slags with

SiO_2	Al_2O_3	CaO	FeO	K_2O
46–50	16–18	16–22	4–6	4

at a temperature as high as 1500°–1550°, are fairly thin but become very viscous even at about 1300°, some 100° above the beginning of crystallization.

The same also applies to slags as

SiO_2	Al_2O_3	CaO	MgO	FeO
46–50	14–18	7–13	3–5	about 20

which at about 1300°–1400° are rather viscous in spite of the high percentage of FeO.

Feldspars.—According to the investigations of the Geophysical Laboratory of the Carnegie Institute, orthoclase (microcline) and albite are characterized by extremely high viscosity just above the melting-point. It is so great, and at the same time the speed of the melting so slow, that these minerals, as well as quartz, may be superheated for a while to some degrees above the theoretical melting-point without melting.[1] On account of the extremely high viscosity of microcline, this mineral has for more than 100 years been used as a glaze for porcelain. Melted microcline is extremely viscous, even when heated to several hundred degrees above the melting-point.

Melted anorthite (melting-point 1550°), on the other hand, just above its melting-point is medium thin, both according to the experiences of the Washington Institute and of myself. The melts lying between Ab and An show intermediate viscosity.

Melted *SiO_2* is extremely viscid, and silicate melts with more than 60 per cent SiO_2 and the remainder mixtures of various bases (CaO, MgO, FeO, Al_2O_3, etc.) show increasing viscosity with increasing percentages of SiO_2.

In short, numerous observations indicate that the viscosity which at a certain temperature characterizes a complex silicate melt containing several components, as SiO_2, $KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$, $CaMgSi_2O_6$, etc., may be *derived from the viscosity which is characteristic of each of the components*. But the viscosity is hardly a linear function of the viscosity of the components.

As to the *alkali-silicates*, we refer to the investigations of Greiner. Here it may be pointed out, however, that K_2SiO_3 (alone or with an admixture of SiO_2) is considerably more viscous than the corresponding soda-silicate, and potassium-glass is, as is known, considerably more viscous than soda-glass. According to Greiner,

[1] See Day and Allen's well-known Feldspar studies (1905).

FeO, MnO, Fe_2O_3, and MgO (in the order mentioned) reduce the viscosity of $Na_2SiO_3 \cdot SiO_2$, while CaO and Al_2O_3 increase the viscosity (Al_2O_3 most strongly).

Applied to petrography it will appear from the above that melted (anhydrous) granite, quartz-porphyry, rhyolite, and obsidian at one atmosphere pressure are extremely viscous, even heated to 100°, 200°, or 300° above the beginning of the temperature of crystallization.

Molten (anhydrous) alkali-syenite, trachyte, and phonolite are still rather viscous, presumed one atmosphere pressure. Molten (anhydrous) gabbros are somewhat more thin, and basalts and related rocks rich in iron are rather thin.

The statements above are valid for molten anhydrous masses, or generally molten masses without dissolved light volatile compounds,[1] at one atmosphere pressure.

As to the *direct influence of the pressure*, reference may be made to Johnston and Adams in the *American Journal of Science*, XXXV, 226–31. The result is "that the effect of uniform pressure is always to increase the viscosity (water and certain dilute aqueous solutions, both of low temperature, excepted)."

According to this it must be supposed that the direct effect of the pressure is to increase the viscosity of the silicate melts. However, more important in many cases is the *indirect* effect of the pressure since the content of the magma of *dissolved light volatile compounds* is increased with the pressure, and these volatile compounds (H_2O, etc.) reduce the viscosity to a very considerable degree.

This applies especially strongly to granitic magmas which according to geological experience must have been rather thin, and still more to granite-pegmatite magmas which even at so low a temperature as about 700°–800° must have been especially thin on account of their relatively rich content of H_2O, etc.

The effusives, on the other hand, must as a rule have contained much less H_2O, etc., and their degree of thinness, at least in many

[1] I do not here take into consideration that the silicate slags from, e.g., a blast furnace or a matte-smelting contain dissolved a very small quantity of gas, which at least to a substantial extent escapes partly before the beginning of the crystallization and partly on an early stage during the process of crystallization.

cases, may be measured approximately by the viscosity valid to the dry melts.

According to this we find that basalt magmas commonly have flowed out in quite thin streams, which may have covered very large areas, even several tens of thousands of square kilometers, while acid rocks, especially rhyolites and related acid effusives, often, but not always, form domes.

We will here also mention another point of great geological importance. As maintained by R. A. Daly in his *Igneous Rocks and Their Origin* (1914), among the *deep-seated* rocks the *acid* rocks (granite and granodiorites) have an extension several times as large as the basic rocks (with the gabbros as the most important representative). The contrary is the case with the *effusives* since here *basaltic* (and pyroxene-andesitic) rocks quantitatively are much more important than rhyolites. I consider from my own geological experience, that Daly is right in this view, but I do not agree with Daly's explanation.

We must suppose that the magmas of the granitic deep-seated rocks generally contained a much larger quantity of the light volatile compounds than the magmas of the gabbroic rocks, and consequently that the temperature at the beginning of crystallization compared with that of the anhydrous melts was decreased much more for the granites than for the gabbros.[1]

When an *acid* (or granitic) magma, at the temperature of the upper limit of the crystallization interval (see the next chapter), comes under a lower pressure, by the passage to the surface of the earth, a great part of the light volatile compounds will escape. By this the temperature of crystallization increases and at the same time also the viscosity increases; the latter even to a considerable degree. The magma, in the first stages of crystallization will under these circumstances become so little movable or so viscous that part of it will never reach quite to the surface, and part of it will do so only under favorable conditions. For the *basic* (gabbroic or basaltic-andesitic) magma we must also assume some escape of the light volatile compounds by the passage to the surface. This is of less importance, however, since the volatile components here

[1] See their *Journal* for 1922, pp. 664–71.

were present in smaller quantities. In addition to this, as the crucial point is the fact that basic magmas with relatively small or no content of light volatile compounds are considerably more fluid than are the acid with the same amounts. Thus the basic magmas, even if they were much less extended in the deep-seated basins than were the acid, must reach the surface in much greater quantity and form much larger flows.

The anorthosites and the almost pure olivine rocks (dunites), according to my opinion, must be explained by the extremely high temperature of crystallization of these rocks. The magmas would consequently be cooled at once to quite advanced crystallization as they were pressed as dikes into the surrounding colder rocks. Thus the magmas of these rocks could not get to the surface and could consequently not form flows.

As treated in my work *Die Sulfid-Silikatschmelzlösungen* (1917), molten FeS, alone or with some NiS, PbS, Cu_2S, etc., is characterized by being considerably thinner than even the thinnest silicate melts. As to the geologic consequences of this, I refer to my earlier publications on the genesis of the nickel-pyrrhotite deposits.

ON THE SIZE OF CRYSTALS AND THE RATE OF CRYSTALLIZATION

Many investigators in their synthetic experiments have confined themselves to melts in a platinum crucible with a comparatively small quantity of silicate as, e.g., 10–20 gm. (or about 4–8 $cm.^3$). In consequence only quite small individuals have resulted, thereby producing a wrong conception of a slow rate of crystallization for the rock-forming minerals.[1]

If we wish to obtain from experiments a correct idea as to the size of the minerals and the rate of crystallization, we must operate with sufficiently *large* molten masses. Even with a duration of crystallization of only half an hour we may get *very large* crystals,

[1] For example we may quote C. Doelter, *Phys. chem. Mineralogie* (1905), p. 108: "Unter normalen Verhältnissen würde ein etwa 10 bis 20 mm. langer Augitkrystall unter der Voraussetzung dass die Krystallizationsgeschwindigkeit pro 1 Minute 0.001–0.002 mm., wie es die meisten Versuche ergeben, beträgt, 200 Stunden brauchen." In fact, the rate of crystallization for augite (diopside) from a pure melt, as will be discussed below, is about 1 mm. (along the *c* axis) per minute, thus 500–1,000 as much as indicated by Doelter.

assuming (*a*) that the crystallization takes place in a very thin fluid silicate melt, and (*b*) that the mineral crystallizes from a solution that is of a percentage of 100, 90, 80, or at least not below 70.[1]

I will give some measures of the size of crystals in some smelting products, slags, etc.

Diopside.—In one of my earlier melting experiments with almost iron-free $CaMgSi_2O_6$ (containing at most 1.5 per cent FeO), thus in a melt of practically 100 per cent of $CaMgSi_2O_6$, the time of crystallization (at 1336°) of a melt of 16 kg. (16,000 gm.), according to pyrometer measurements, amounted to thirty-one minutes. There resulted, hereby, individuals of a length of 30 mm. ($\pm c$), locally, perhaps, a little longer, and in druses were found freely developed columnar crystals 25 mm. long parallel to *c*, 9–10 mm. parallel to *a*, and 7 mm. parallel to *b*.

In the common iron furnace, slags cast in slag-stone molds about 0.4×0.3×0.25 m. in size, where the crystallization according to pyrometer measurements requires about thirty to forty minutes, I found in slags with about 75–80 per cent augite, freely developed crystals of diopsidic augite 18–20 mm. long parallel to *c*, 9–11 mm. parallel to *a*, and 6–8 mm. parallel to *b*.

Pseudowollastonite.—A melting experiment performed by me, in melting 3.5 kg. of pure $CaSiO_3$ (with a time of crystallization of about fifteen minutes), gave as a result thin tabular crystals 18 mm. long measured parallel to the base, with some individuals a little longer.

In slags with about 60–70 per cent pseudowollastonite with a period of crystallization of about thirty minutes, thin tabular crystals with a base of a length in one case of 7 mm. and in another case of 8 mm. were freely developed.

The melilite minerals.—The largest melilite crystals and the largest slag crystals that I have seen, on the whole, I found in 1913 in a basic slag, rich in CaO and with some Al_2O_3 and FeO, from a remelting process at one of the Mansfielder works. In the druses here appeared tabular crystals (001) (100) with lengths parallel

[1]Under otherwise equal conditions, the size of crystals is a function of the quantity of the segregated mineral (see *Die Silikat-Schmelzlösungen*, II (1904), 164).

to the base of 49, 50, 51, and in one single crystal up to 56 mm., and of a thickness parallel to *c* of 13–14 mm. (Fig. 54). The slags contained about 90 per cent melilite. It may be noted that a melilite melt with some per cent of FeO is very thin.

In another slag, also containing melilite, rich in FeO (from Przibram, 1913), the lateral edge of the quadratic crystals measured 22 mm.

The largest crystals of *åkermanite*, found by me in a slag containing about 90 per cent crystallized mineral (with about 4 per cent Al_2O_3), occurred in thin tabular crystals (001) (100) with a little (110). They showed a length parallel to the base of 19, 21, and occasionally even 24 mm. and a thickness of 2–2.5 mm. In slags with 60–70 per cent åkermanite, the tabular breadth is commonly 5–10 mm.

FIG. 54.—Large melilite crystals in slag. (Two-thirds natural size.)

My largest *fayalite* crystal (tabular along 010) shows a tabular size, 25×39 *mm.* In fayalite slags with 70–80 per cent fayalite, a tabular length of 25–30 mm is very common. Similar dimensions are also constantly met with in manganese-fayalite, $(Mn, Fe)_2SiO_4$.

Slags with only 40–50 per cent *olivine* $(Mg,R)_2SiO_4$, (where R = small quantities of Mn,Fe, etc.) show tabular crystals (on 010) about 7–14 mm. Smelting masses consisting of almost pure Mg_2SiO_4 I have not examined.

The freely developed crystals of *rhodonite*, $(Mn,Fe)SiO_3$ or $(Mn,Fe)\ SiO_3$, in the druses of slags with 65–80 per cent rhodonite, commonly show a length of 12–15 mm., sometimes up to 20 mm.

And the individuals of rhodonite in melts with about 80–95 per cent rhodonite may reach a length of 37–40 mm.

In a melt of 100 per cent $CaMgSiO_6$, diopside of a length ($\perp c$) of 30 mm. crystallized in the course of thirty-one minutes. This gives a rate of crystallization of *about* 1 *mm.* (*or* 0.97 *mm.*) *per minute.*

For the largest crystals of pseudowollastonite, melilite, åkermanite, fayalite (Fe_2SiO_4), manganese-fayalite [$(Mg,Fe)_2SiO_4$], and rhodonite [$(Mg,Fe)\ SiO_3$], commonly crystallized from solutions of 75, 80, or 90 per cent (or in one single case of even 100 per cent), we get a corresponding rate of crystallization, viz., about 1 mm. per minute. In fayalite, and almost certainly in manganese-fayalite, the rate is somewhat more than 1 mm. per minute, measuring the greatest length of the crystals.

All the minerals mentioned above that reach lengths of 20, 30, exceptionally even of 40 *or* 50 mm., crystallized (in the course of about half an hour) from very *thin fluid melts.* If, as a contrast to this, we take extremely viscous silicate melts as, e.g., $KAlSi_3O_8$, $NaAlSi_3O_8$, and SiO_2, there are formed, even if they are kept for one or more days just below the melting-point, crystals of only extremely small dimensions.

The *rate of crystallization*, no doubt, is a function of several factors, and one of the most important of these is the *degree of viscosity.*

All the foregoing minerals examined by me, which in the melted phase are very thin, are characterized by so great a *tendency to crystallization* that, from a solution of 80–100 per cent, they crystallize even under a very quick cooling. If, thus, we pour, e.g., melted Fe_2SiO_4, $(Fe,Mn)_2SiO_4$, $CaMgSi_2O_6$, or melted åkermanite into a calorimeter pipe, where the cooling from the melting temperature to usual room temperature requires only eight to ten minutes, and where the period of crystallization has a duration of only about one minute, we as a rule at least get some mineral segregated.

In very viscid molten masses it is quite different. To cause crystallization here, we must keep the molten mass heated just below the melting-point (or below the curve of crystallization) for

hours, days, or with extremely viscid masses, perhaps even for weeks.

This general fact has *inter alia* an important application to the *relation between the time of crystallization and the viscosity* in smelting masses of approximately *eutectic* composition. In the adjacent diagram (Fig. 55), *kl* indicates a certain viscosity and *mn* at lower temperature a higher degree of viscosity of the melt. When undercooling is not taken into consideration, the mineral *a* in a smelting mass of composition u_1 will begin to crystallize at t_1, in a

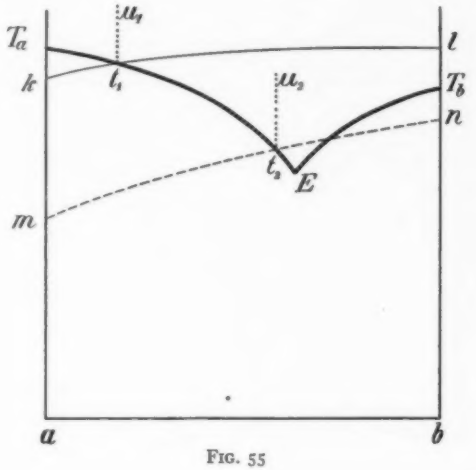

FIG. 55

smelting mass of composition u_2, on the other hand, at t_2—thus at a stage when the molten mass has grown more viscous. It is the same if in both cases we presume the same degree of undercooling. If the cooling proceeds at the same rate, we will get quite large crystals and some glass from the u_1 melt, while from the u_2 melt we will get glass with a small quantity of small crystals. At a still quicker rate of cooling, no crystallization at all takes place in u_2, so that it solidifies entirely as glass.

That crystallization actually takes place, as here theoretically explained, I have proved experimentally in my previous works.

In general, we may set up the thesis: *Compositions of eutectic or almost eutectic character further the formation of glass.* This principle really gives the general foundation for glass technology. At a medium rate of cooling of molten pure $CaSiO_3$, of pure Na_2SiO_3, or K_2SiO_3, respectively, crystallization takes place. A eutectic or nearly eutectic mixture of $CaSiO_3$ and Na_2SiO_3, respectively K_2SiO_3, gives, on the other hand, with fairly quick cooling, glass only, without any formation of crystals. If also, as in the manufacture of glass, a third component, SiO_2, is added, the viscosity is considerably increased even at high temperatures. On cooling a melt nearly of the composition of the ternary eutectic $CaSiO_3$: Na_2SiO_3:SiO_2 to a point on the melting surface (or in view of the supersaturation somewhat below the melting surface), the viscosity is so considerably increased that with medium quick cooling no formation of crystals can take place, i.e., glass results.

The principle here treated has a considerable influence on the structure of the geologically, relatively quickly cooled dikes and flows. By progressive crystallization at decreasing temperatures, the viscosity of the residue melt generally increases. The consequence is a fine-grained ground mass, or with still quicker cooling, a total restraint of crystallization, so that the remainder solidifies as glass. Melts rich in iron and basic (with about 50 per cent SiO_2) are not nearly so viscous as those poor in iron and acid (with about 68–75 per cent SiO_2). Because of this, glass basis usually plays a more important part in the quickly cooled acid rocks than in the basic.

Melts of anchi-eutectic composition poor in H_2O may be extremely viscous at the relatively low temperature of crystallization which characterizes them. With relatively quick cooling, consequently, the crystallization will be entirely or nearly entirely restrained. Thus it is no accidental circumstance that by far the most of *obsidians* have nearly the chemical composition of the granitic eutectic. Many, perhaps even the most, obsidians contain 72–76 per cent SiO_2 and between 0.3 Or:0.7 Ab+*An* and 0.5 Or:0.5 Ab+*An*. They thus even approach the "ternary" granitic eutectic, having an especially low temperature for the interval of crystallization, and thus also an especially high viscosity at the stage where

crystallization might take place. (See the chap. pp. 93–100 in my treatise on anchi-monomineralie and anchi-eutectic rocks, 1908.)

In *highly viscous* melts, inoculation causes no crystallization. Thus rhyolites contain glass mainly of the composition of quartz and feldspar, even though crystals both of quartz and feldspar have been segregated.

The entire lack of glass in deep-seated rocks is an evidence of quite extraordinarily *slow* cooling. The crucial point for the distinction between the deep-seated rocks, on the one hand, and the effusives and dikes on the other, is not pressure, but *time*. Many dikes have been solidified at very great depths, thus under the same pressure as the adjacent deep-seated rocks.

Granites of practically the same chemical composition show at times considerable variation in the size of grains. Thus the feldspar individuals in some granites have an average length of 0.3–0.5 cm., in others 1–1.5 cm. The relatively coarse grained granites form at more places much smaller areas (of, e.g., 10–50 km.^{2}) than those of finer grain (with areas of, e.g., 100–500 km.^{2}). The decisive point for the size of the grain thus can neither be duration of crystallization nor solidification in more or less great depth. The cause may, I suppose, be due to the fact that the magma of the relatively coarse grained granites had less viscosity on account of a higher content of H_2O, etc.

In this connection, it may be noted that the hypersthene-granite from Birkrem, etc. in the Ekersund District is medium fine grained, which may be due to the fact that the magma of this granite, as stated above,[1] contained relatively little H_2O. It might be interesting to examine whether all hypersthene-granites are characterized by only medium size of grains.

The extreme size of the grains of the pegmatite dikes of granite, augite- and nephelite-syenite, etc., proves, as maintained by many investigators, an extreme fluidity of the magma, depending on relatively large contents of H_2O, etc. At one atmosphere pressure the rate of crystallization of many minerals, by the segregation from *very thin* melts, is on an average 1 mm. per minute or 3 cm. per half hour, corresponding to about 1.4 m. per day (twenty-

[1] The *Journal of Geology*, XXX, 670..

four hours). Even though these figures cannot be transferred directly to pegmatite dikes formed under great pressure, it is evident, at any rate, that their crystallization did not necessarily require an exceptionally long time, speaking geologically. Granite-pegmatite dikes, commonly only 5, 10, 20 m., seldom as much as 50–100 m. thick, must have solidified in much shorter time than the rock in the large granite fields.

UNDERCOOLING (SUPERSATURATION)

The degree of supersaturation necessary to crystallization is a function of *time* and *viscosity*, and of other general factors. Furthermore there will perhaps also be involved a quality specific to each mineral.

For the melting of quite small quantities as, e.g., 10–20 gr. in platinum crucibles, the supersaturation necessary to crystallization is as a rule quite considerable. It is otherwise with fairly thin melts when we work with quantities of, e.g., 10–20 kg.

The explanation may probably be found in the fact that, after a certain degree of supersaturation in the first cooled peripheral parts (the surface or the walls of the crucible) diminutive crystals are formed, which in fairly thin melts abolish the supersaturation in the inner, somewhat more heated parts of the molten mass.

We shall illustrate this by an example (see *Die Sulfid-Silikatschmelzlösungen*, I (1919), 75) concerning the melting in graphite crucibles of different quantities of $(Ca,Mg)_4Si_3O_{10}$ (with 0.7 Ca:0.3 Mg) from which mainly åkermanite crystallized.

Two experiments were made, in one case with 19 kg., and in the other with 1.1 kg. The curve of melting (transition from solid to liquid phase) was found to give 1290° at the beginning and 1310° (or 1312°) at the end.

The curve of crystallization (transition from liquid to solid phase) gave (*a*) with 19 kg., period of crystallization twenty-five minutes, from 1310° to 1290°; (*b*) with 1.1 kg. period of crystallization six minutes, from 1280° to 1240°. The crystallization of the 19 kg. melt thus took place at the same temperature as the melting, i.e., *the crystallization took place without noticeable undercooling*. In the test with only

1.1 kg., on the other hand, there was found to be (by more parallel measurements) an undercooling of 30°–40°. In *very thin silicate melts* of sufficiently large quantity and with sufficiently slow cooling so that the crystallization lasts at least one or several hours, the crystallization, no doubt throughout, takes place with only an extremely small degree of undercooling. In *very viscous* melts, on the other hand, the undercooling may play an extraordinarily important part, even when very large molten masses are involved.

In normal striated deep-seated rocks I do not know of any structural element which indicates any traceable supersaturation. This must depend on the fact that they were cooled so slowly that the crystallization took place with quite insignificant supersaturation. To a certain degree it is otherwise with orbicular granite, diorite, etc., having concentric orbs. Here the successive shells from the center to the periphery (as I have shown in *Tscherm. Min. Petrogr. Mitt.*, XXV (1906), 396–403) may be explained under the supposition that the crystallization first began after some undercooling, especially along the eutectic boundary lines. This orbicular structure of the deep-seated rocks occurs as a rule only as a border phenomenon near adjacent older rocks, and this must be due to the fact that the cooling here took place somewhat quicker than in the central parts of the eruptive fields.

In the still more quickly cooled dikes and effusives, the supersaturation generally has played a certain rôle, as is indicated by partial resortion on account of supersaturation (see a following chapter). In very viscous dikes and effusives rich in silica, the supersaturation may have been of very considerable importance.

ON THE EQUILIBRIUM BETWEEN THE SOLID AND THE LIQUID PHASE OF MIX-CRYSTAL COMPONENTS

In *dikes* and *effusives*, the plagioclases, pyroxenes, etc., may show, as is well known, a zonal structure, and the "second generation" of the plagioclase has as a rule a different composition (a higher percentage of Ab) from the "first generation." This comes from *an absolutely lacking or a more or less incomplete equilibrium* between the segregated mix-crystals (or the first "embryonal" mix-crystals together

with the mix-crystals of the succeeding crystallization) and the corresponding components in the liquid phase.[1]

If we take plagioclase as an example, there will first crystallize from a magma with the plagioclase components in the proportion, e.g., 58 An:42 Ab—not only in melts consisting of pure An+Ab, but also in magmas with more or less of other components—[2] an embryonal mix-crystal with a composition about 84 An:16 Ab. The succeeding mix-crystals will contain gradually decreasing amounts of An and increasing amounts of Ab with absolutely lacking equilibrium say up to 30 An:70 Ab, and at last we may get thin zones with still less An and still more Ab. These last zones, as a rule, however, are in such small quantity that they may be entirely overlooked or may be seen only with difficulty under the microscope.

In order to decide if the equilibrium between the solid and the fluid phase is absolutely lacking or only more or less incomplete, we may start with a rock having an average proportion An:Ab, determined by the chemical analysis, and examine the composition of the "first" mix-crystal. For this purpose we may with some corrections, however, use the data given in my study on "Die physikalisch-chemischen Gesetze der Krystallisationsfolge in Eruptivgesteine,"[3] where I calculated from chemical analyses, the proportions of Or:Ab:An in many rocks (especially andesites), as well as the composition of the "first" phenocryst in the same rocks. I will give an extract from this table, recalculating Or:Ab:An to only Ab:An. The values following are the calculated quantities of An in the sum of Ab and An, both in the rock and the in phenocrysts. Further, I give the theoretical composition (or the An content) of the first plagioclase crystallizing in an Ab+An melt, according to the scheme delivered by Bowen (1913).

Percentage of An in Ab+An, (*a*) in the total rock, (*b*) in the phenocryst,[4] and (*c*) theoretically.

[1] I refer to the general explanation in *Die Silikat-Schmelzlösungen*, I and II (1903 and 1904), and to numerous later treatises by various authors.

[2] See this *Journal* for 1921, pp. 325, 327.

[3] Tscherm. Min. Petrogr. Mitt., XXIV (1905), pp. 503–4 and 512.

[4] The numbers refer to my table in 1905.

This review proves, in spite of the sources of error connected with the computation, especially of the first two rows of figures, that the "first" phenocrysts in the andesites, etc., here considered never contain quite as much An as the theoretical calculation requires. The phenocrysts indeed, in many cases, may be zonal; they may consequently contain in the kernel a little more An than the chemical analyses of the whole phenocrysts show. But even if we take this into consideration, the *kernel* of the phenocrysts will always or almost always contain not quite as much An as the theoretical calculation requires. That is to say, at the beginning of crystallization, as long as the phenocrysts were extremely small, the equilibrium between the solid and the fluid Ab+An phase was very incomplete, but not absolutely lacking. Under the microscope,

	Number							
	15	14	5	4	18	13	6	7
In the rock	42	43	42	46	32	37	47	42
In the phenocryst	69	68	62	62	56	56	60	57
Theoretically	76.5	76	76	78	70	73	78.5	76

we observe that the zonal structure of the plagioclases, as well as of the pyroxenes, etc., is in general more pronounced in the periphery than in the kernel of the individuals.

Concerning the dikes and flows, we may thus maintain as the crucial point that the equilibrium between the solid and the fluid mix-crystal phase was lacking to a very great extent. At the beginning of the crystallization, as long as the crystals were quite small, and at a stage with a relatively high temperature and consequently with a moderate viscosity of the magma, we may indeed assume a limited equilibrium. But at the later stages of the crystallization, viz., with larger crystals and at lower temperature and a higher degree of viscosity of the residual magma, only very incomplete equilibrium occurred.

As well known, we occasionally observe in the plagioclases of dikes and flows a *recurrence* of zonal structure. For example, around a series of zones, showing decreasing An, there may suddenly occur a zone with more An and less Ab. This probably depends

upon a downward sinking of the crystals.[1] If a zonal plagioclase sinks in a flow with more advanced crystallization in the upper than in the lower part, consequently, to where there is relatively more An than Ab, the new zone deposited on the crystal will contain relatively less Ab than the outer zone of the original crystal. Whether this explanation is right or not, may be decided by a study of plagioclases and other mix-crystals from the upper as well as from the lower part of the same flow.

Turning now to *deep-seated rocks:* the plagioclases, pyroxenes, etc., in most cases do not show zonal structure at all. This phenomenon is here exceptional, and even where shown the zonal structure and the chemical difference between the "first" and the "second" generations are not so prominent as in dikes and flows.

I thus found in looking over many thin sections of norites that only in a couple of cases did the outer zone of the hypersthene show a higher, though only a little higher, percentage of iron ($Fe\ SiO_3$) than the central part.

As to the plagioclases we will mention two cases: The extremely coarse-grained porphyritic labradorite-norite, with phenocrysts of labradorite up to 15–18 cm. long and 6–8 cm. broad, described in my treatise in *Quarterly Journal of the Geological Society* (1909), and mentioned in this *Journal* for 1921, page 439, shows the following proportion between An and Ab, the small quantity of Or not being taken into consideration.

In the rock as a whole (or in the magma)	58 An:42 Ab
In the phenocrysts	65 An:35 Ab
In the ground mass	55 An:45 Ab

In a magma with the plagioclase components in the proportion 58 An:42 Ab, the first crystallizing plagioclase, according to Bowen's scheme, must have the composition 84 An:16 Ab (Fig. 56).

During the entire first stage of crystallization, from $An_{84}\ Ab_{16}$ to $An_{65}\ Ab_{35}$, equilibrium between the solid and the liquid phase prevailed, i.e., the already segregated plagioclase at length transformed its composition. Then the equilibrium in the actual case ceased, probaby due to the fact that the crystals first segregated

[1] See my treatise in *Tscherm. Min. Petrogr. Mitt.*, XXIV (1905), 517, and the therein cited previous treatises.

had such considerable size as to impede the equalization of Ab:An in the solid and the liquid phase.

As another example we refer to the orbicular quartz-norite from Romsaas (described in this *Journal* for 1921, pages 430–35), the plagioclase, here also disregarding the small quantity of Or, of an average composition of An_1 Ab_1 (or An_{52} Ab_{48}), with the kernel of An_{58} Ab_{42} and the exterior of An_{45} Ab_{55}, locally even up to An_{38} Ab_{62}. This orbicular norite occurs in a quite small eruptive field

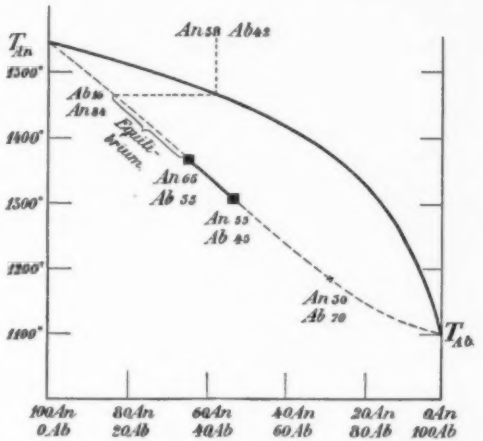

FIG. 56

close to the surrounding gneiss, which caused the time of cooling to be somewhat quicker than is common to deep-seated rocks.

Further I refer to the description given by V. M. Goldschmidt[1] of the "Trondhjemite" generally containing 69–76 per cent SiO_2, 16–13 per cent AlO_3, 3–1 per cent Fe_2O_3+FeO, 1–0.2 per cent MgO, 3.5–1.7 per cent CaO, 6.5–4.5 per cent Na_2O, 2.5–0.5 per cent K_2O, etc. The kernel of the plagioclase shows 20–32.5, most commonly 24–29 per cent An, and the outer zone about 16 per cent An, often with recurrence of basic and acid zones. That the zonal structure of the plagioclase of this rock is more pronounced

[1] Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegens (Kristiania: Vidensk-Selskob, 1916).

than usual with the plagioclase of the deep-seated rocks may perhaps be due to the acid composition of the magma, which at a somewhat advanced stage of the crystallization may have been rather viscous.

The great difference in equilibrium between the solid and the fluid mix-crystal components, in dikes, and flows, with very incomplete, but as a rule not absolutely lacking equilibrium on one hand, and deep-seated rocks in some cases with medium, though mostly with practically complete equilibrium, on the other hand, must be due to the great difference of the *time* of the crystallization.

H. E. Boeke states in his *Grundlagen der phys.-chem. Petrographie* ([1915], p. 99) that: "Diese, eine Diffusion im festen Zustande erforderliche Änderung findet namentlich bei Silikaten nur mangelhaft statt." This is so far correct since this diffusion goes on much more slowly in silicates than in metals, but the diffusion in the silicates may become very extensive or even complete, when, as in many deep-seated rocks, there was sufficient time and the magma was rather thin fluid.

[*To be continued*]

REVIEWS

A Summer in Greenland. By A. C. SEWARD. Cambridge University Press, 1922. 8vo, pp. 100, pls. 47, maps 2.

This is a charming little book by a very capable student of ancient and modern plant life. The setting of the story is one of unique interest, present and past, physical and biological. The points of interest are many and are skilfully touched. Naturally they center where the author's competency is greatest, on the present and past plant life, especially as West Greenland is biologically the most unique of all Arctic regions.

The treatment of the present flora goes much beyond enumeration, classification, and similar formal and statistical matters, and touches upon adaptations, migrations, and relations that concern the life and death of plants in their battle with conditions that are inhospitable to the casual view, but which are not without their advantages to organisms that have succeeded in seizing upon these and using them.

The author's comparisons of arctic and of tropical modes of growth bring into vivid contrast the struggle for life when it is against adverse physical conditions, and the scarcely less severe struggle for life when it is against an overstress of biologic competition.

The author brings out sharply the great contrast between the development of plants in the Arctic and in the Antarctic regions respectively. The passage adds so much to the contrasts cited in the climatic paper on an earlier page of this number of the *Journal* that it is here quoted:

> Not a single flowering plant has been discovered within the Antarctic Circle. The most southerly representative of the flowering plants, over four hundred of which occur in Greenland, is a grass (*Deschampia antarctica*) which was found in the sub-Antarctic region and reaches its southern limit in lat. 62° S., a position corresponding to that of the Faroe Islands and the south of Finland in the northern hemisphere [pp. 71–72].

Other statements of the book are very opportune at this time when there is a disposition in certain quarters to discredit the conclusions reached long ago by Heer, Etheridge, and other early students, that strangely mild climates prevailed in the polar regions in certain geological periods, and the similar conclusions reached more recently on the basis

of new data by Nathorst, Schuchert, and others. Seward, whose standing and competency need no comment, makes it clear that he entertains no doubt about the reality of such warm climates in the regions he visited and in the ages he specifies. Some of his statements are not only worthy of quotation, but of emphasis:

> The cliffs on some parts of the coast are built up of limestones, sandstones, shales, and old pebble beaches containing the remains of animals and plants characteristic of several geological periods and clearly indicating climatic conditions within the Arctic Circle much more genial than those at the present day. Even in the extreme north, on the shore of the Polar Sea, limestone rocks have been described by the Danish geologist, Koch, as veritable coral reefs of the Palaeozoic era.
>
> The most northerly point at which fossil plants have been found is on the east coast of Greenland, between lat. 80° N. and 81° N. Fragmentary remains of plants were found by the Denmark Expedition of 1906–1908: these were described by the late Professor Nathorst, who recognized them as members of a flora which preceded that of our Coal Measures. The locality where these plants were found is nearer to the North Pole than any previously recorded for Carboniferous plants [p. 26].
>
> The fossil-bearing rocks it was our aim to investigate are exposed along the shore and in the ravines of Disko and other islands and especially on the Nûgssuaq Peninsula. Most of them were deposited during the Cretaceous period; others are Tertiary in age. Slabs of rock detached with the aid of a pick-axe from the side of a ravine where the hills are made of a succession of sheets of sediment—the sands and muds of some ancient lake or lagoon—are found to be covered with the clearly outlined impressions of large leaves like those of the Plane or Tulip tree, fronds of ferns hardly distinguishable from species (of the genus *Gleichenia*) living to-day in tropical and sub-tropical countries; there are also twigs of Conifers, some of which are almost identical with those of the Mammoth tree (*Sequoia* (*Wellingtonia*) *gigantea* now confined to a narrow strip of the Californian coast), and massive stems of forest trees. None of the leaves preserved in the Greenland rocks have a greater fascination for the student of the past history of living plants than those of the genus *Ginkgo*. This genus is now represented by a single species, the Maidenhair tree (*Ginkgo biloba*), which is sometimes said to occur in a wild state in China, though it is probable that even in China and Japan, where it grows abundantly, it is only as a cultivated tree associated in the oriental mind with some religious symbolism. *Ginkgo* is often planted in gardens and parks in Europe and America and is distinguished from all other trees by its broad and often lobed, wedge-shaped leaves. Fossil leaves, some indistinguishable from those of the sole survivor of this ancient genus, have been found in the Cretaceous sediments on Upernavik Island (Map *B*), in sedimentary rocks associated with basaltic lavas at Sabine Island (lat. 75° N.) on the east coast of Greenland, at several

localities within the Arctic Circle, also in many other regions of both the Old and the New World. These records afford an exceptionally striking illustration of the possibilities offered by a study of the herbaria of the rocks of connecting the present with the past, of following the wanderings over the world and of tracing the rise and fall in their fortunes of still living members of the plant kingdom. These fragmentary relics, "The ghostly language of the ancient earth," suggest problems that are more easily stated than solved.

Many records of ancient floras are readily decipherable, foliage shoots and clearly outlined leaves showing the finest veins, the plant substance changed into a thin film of coaly substance which on treatment with certain chemicals reveals under the microscope details of the surface cells and throws light both on the affinities of the plants and on their relation to the world in which they lived. The minute structural details of petrified wood after it has been cut into transparent sections can be examined with as much thoroughness as those of a living stem; the living substance has gone, but the framework remains and through it we obtain an insight into the mechanism of the plant which was alive some millions of years ago. Other fossils are but "age-dimmed tablets traced in doubtful writ," and these add zest to the task of interpretation [pp. 27–29].

One of the most convincing and impressive arguments in support of the prevalence of an almost, if not quite, tropical climate in Greenland during the Cretaceous epoch is furnished by portions of large leaves and pieces of the fruit of a Breadfruit tree discovered by members of a Swedish expedition in 1883 on the coast of Disko Island and described by the late Professor Nathorst, who was well known as an Arctic explorer and an exceptionally able student of the floras of the past. The Breadfruit, *Artocarpus incisa*, which the Greenland fossil closely resembles, is cultivated practically all over the tropics and is native in some of the Pacific Islands [p. 31].

The little book is full of charming pictures, literary as well as photographic, and it is studded all through with substantial things well worth knowing.

T. C. C.

Geomorphology of New Zealand, Part I, Systematic. By C. A. Cotton. Wellington, N.Z.: Dominion Museum, 1922. Pp. x+462, pls. 1, figs. 442.

One of the beauties of the science of geology is the wide applicability of its underlying principles. A generalization is developed in one country where conditions or methods of study are particularly favorable, then later it is used by geologists in far distant countries to solve problems hitherto obscure. Thus its validity becomes more firmly established. The chief interest to American geologists in this work by Professor

Cotton is the success with which he applies certain of Davis' principles of physiography to the interpretation of New Zealand land forms. His aims are well stated in the following sentence from the Preface:

> In the hope of setting forth these principles in a convincing manner and thus popularizing in New Zealand the fascinating study of land forms, the present work (Part 1) is cast in the form of a textbook of geomorpho'ogy for New Zealand students and general readers.

In pursuance of this plan, the history of the science of geomorphology is traced from its beginning early in the nineteenth century to the present time. In this development, the work of American geologists has been given a very important place. Following Davis, the distinction is drawn between the empirical and explanatory methods of description of land forms, and the great superiority of the explanatory method is set forth.

The central theme around which the subject-matter is arranged is the concept of the erosion cycle. Several chapters are devoted to the normal erosion cycle, and each stage is illustrated by New Zealand examples, many of them from the author's own work. Complications in the normal cycle claim a share of attention, as does also the arid cycle. A comparatively recent extension of the principle of the erosion cycle is its application to glacial action. As glaciation is a notable feature in New Zealand, it naturally receives rather full treatment. Briefer treatment is accorded to volcanoes and igneous activity, which are considered as interruptions of the normal cycle. There is no lack of igneous phenomena in New Zealand and some excellent illustrative material is here incorporated. The closing chapters deal with the work of waves and the development of coastal outlines.

The organization of material is admirable. The numerous illustrations are in most cases very effective, especially the line drawings. These, together with the writer's lucid and interesting style, make the book very attractive. It should make a valuable addition to any geological library and merits considerable attention from students of physiography in countries other than the one about which it is written.

A. H. B.

Silver Enrichment in the San Juan Mountains, Colorado. By EDSON S. BASTIN. Bulletin 735-D, United States Geological Survey, Washington, D.C., 1922. Pp. 67, figs. 18.

The paper presents primarily some details of silver enrichment in the San Juan Mountains as shown by a study of polished ore specimens. It was not possible for the writer himself to consider exhaustively the

field relations; for facts about these, therefore, reliance was placed largely on the observations of earlier workers in the area.

Typical ore specimens from ten mines of the region near Ouray and Telluride are first described. With the co-operation of Mr. Chase Palmer, a chemical study of the hot springs near Ouray was made, but the neutral waters are high in calcium sulphate and yielded no final conclusions as to their origin.

At several mines it is found that pearceite is a *late* primary mineral, suggesting that in this form the metal has greater solubility than other silver salts found in these ores. A new silver mineral, apparently intermediate between argentite and galena, is noted in several specimens, separating primary galena from secondary argentite. In some of the mines in the Red Mountain district between Ouray and Telluride, replacement results in a gradual substitution of silver and copper for lead, zinc, and iron—a change roughly comparable to the position in the electromotive series of the metals concerned.

In general, these studies seem to show that silver sulpho-salts are important in both primary (hypogene) and secondary (supergene) mineralization. Apparently the sulpharsenides and sulphantimonides of silver tend to be among the later generations of primary minerals. Both downward silver enrichment and the upward transportation of silver minerals take place more readily in neutral or but faintly acid waters. The facts given also illustrate beautifully the importance of relief and erosion in stripping off the enriched zone, as well as the effect of rising solutions, especially those rich in hydrogen sulphide, in retarding the downward progress of enrichment.

More than anything else, however, the facts so well presented illustrate the growing importance of micropetrography of the ores in solving economic problems. To quote the writer:

> The judgment as to the probable success of deep mining in veins rich in silver near the surface should not be prejudiced by preconceived ideas of the importance of enrichment. Each district and in some districts each mine presents a special problem. The method of microscopic study of the ores worked out in recent years offers a method of determining, roughly at least, the relative importance of primary and secondary processes in the deposition of silver ores far in advance of the ultimate test by actual development. The practical value of information of this sort is out of all proportion to the moderate cost at which it may be procured.

Occasionally the reviewer is led to doubt the evidence adduced to prove the secondary character of certain minerals. Thus:

The pyrargyrite and proustite of the ores were apparently deposited after the primary ore had been somewhat fractured. They were not observed intergrown contemporaneously with any of the undoubtedly primary ore minerals. In view of this fact and their apparent playing out with depth, they are regarded as products of downward enrichment.

To the reviewer, it seems that this sort of evidence is rather unsatisfactory as a guide in developing a mine, since the same distribution and lack of intergrowth of the two silver minerals might well be attributed to their irregular deposition from *late* hypogene solutions.

But such minor points are almost negligible. The paper is well illustrated with camera lucida drawings. It is a very real contribution to applied economic geology, and it is to be hoped that the writer will continue with his fruitful studies of silver enrichment.

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Geologie von Mexiko. BY WILHELM FREUDENBURG. Gebrüder Borntraeger, Berlin, 1921. Pp. viii+232, pls. 2, figs. 29, tables.

This publication is a digest of the existing literature on Mexican geology and as such it fills a distinct need. Under section 1, "Summary of Morphology," the author treats of boundaries, coasts, areal extent, orographic elements, vulcanism, and faulting. He then describes in turn the seven physiographic provinces of Mexico and their history, following Warren N. Thayer.

Section 2, which is headed "Stratigraphy and Kinds of Mountains," constitutes nearly half of the volume. Beginning with the Archean, the formations are given brief descriptions and the geologic history interpreted as far as possible from existing knowledge. Considerable prominence is given to the Mesozoic, particularly the Jurassic and Cretaceous. Typical Mexican stratigraphic successions (including also the fossils) are correlated with the European time scale in several diagrammatic sections.

The subject of vulcanism fills most of the remainder of the volume. It is noteworthy that while Tertiary and Quaternary effusives surface a considerable fraction of the whole area of Mexico, the post-Cambrian intrusives are comparatively insignificant. "The Active and Extinct Volcanoes of Mexico"; "Relation of the Tertiary Vulcanism to the Structure"; and "Relations between Volcanoes and Earthquakes" are the subjects of the next three sections, and attest the fact of the great importance of vulcanism in the recent geologic history of Mexico. The mineral deposits of Mexico are given as much space as could be expected in a

brief general treatise. The fairly extensive bibliography of Mexican geology will be of value to many.

A. H. B.

Nomenclature and Description of the Geological Formations of Indiana. By E. R. Cumings. *Part IV, Handbook of Indiana Geology.* Publication 21, The Department of Conservation, State of Indiana, 1922.

This report is one of the six papers brought together in Professor Logan's admirable handbook of Indiana Geology. Professor Cumings' reputation as a stratigraphic paleontologist will lead the experienced geological reader to expect a thorough piece of work in this section and he will not be disappointed. The bibliography dealing with the stratigraphy and fossils of the state, which is an important feature of the work, occupies thirty-six pages. Professor Cumings' intimate knowledge of the fossil faunas of Indiana has enabled him to carry out the formidable task of critically reviewing and summarizing the most pertinent data in the several hundred papers represented in this extensive literature in an admirable manner. His detailed tracing of the history of each of the fifty-eight formation names establishes a sound basis for a stable nomenclature. This careful review of the Indiana formational nomenclature will be of much value to the geologists of adjacent states as well as to those of Indiana. Geologists concerned with the nomenclature of geologic formations may be interested in Professor Cumings' proposal regarding the substitution of Medinan for Oswegan. Professor Cumings draws the Ordovician-Silurian boundary at the top at the Richmond instead of at the bottom, where some paleontologists have proposed placing it in recent years.

The well-planned geologic time scale summarizes, so far as this is possible on a single sheet, the present state of knowledge of the stratigraphy of the state. This important illustration should have had a general title printed on it.

A map showing type localities of geological formations in the Central States and Southern Ontario is a useful feature of the report. It indicates, however, only a small portion of the type localities in this extensive region. A series of geologic sections across Indiana and eight paleogeographic maps illustrate the broader geological features of the state and its past geological history, as interpreted by the author.

The historical and bibliographic features of this paper will make it an indispensable work of reference for stratigraphic paleontologists.

E. M. Kindle

Stratigraphy of the Pennsylvanian Formations of North-Central Texas. By F. B. PLUMMER and R. C. MOORE. University of Texas Bulletin 2132, 1921. Pp. 237, pls. 27, figs. 19.

This work is an important contribution to the literature of American stratigraphy. Its publication was made possible through the officers of the Roxana Petroleum Corporation who were generous and far-sighted enough to recognize that the benefits to science resulting from the presentation of these facts to the geological profession outweigh any possible detriment to their own interests.

The Pennsylvanian rocks of north-central Texas occur as two great inliers which occupy about 7,000 square miles. Because of their isolation from the classic Mississippi Valley section their study has been long delayed, the only earlier publications dealing essentially with their stratigraphy having been written by Tarr, Cummins, and Drake in the early volumes of the Geological Survey of Texas. Recently the discovery of the great petroleum resources of the region has stimulated geologic investigation.

The Pennsylvanian sedimentation in northern Texas began with the deposition of the petroliferous limestone and carbonaceous shale of the Bend group. At the end of this first epoch there was an uplift with folding which resulted in erosion. Then followed thick beds of sand and gravel interbedded with clay making up the Strawn group. These coarse sediments were succeeded largely by the calcareous oozes and marls of the Canyon group. During the latter part of the period there was a long epoch of oscillating levels of the sea during which beds of clay, sand, and limestone were deposited in alternating succession forming the Cisco group.

Of especial interest are the authors' conclusions with regard to the Bend group. On account of its economic importance as a source of petroleum it has received much attention in the past, and its age has been a matter of dispute. The name Bend was proposed for the black shale and limestones which overlie the Ordovician beds at McAnnelly's bend of the Colorado River in San Saba County. Although resting unconformably beneath the coal-bearing Carboniferous sandstones, they contain a preponderance of Coal Measures fossils, and were therefore thought to belong to the Pennsylvanian. These beds were first referred by Tarr to the Mississippian, then as a result of Cummins' work, they were transferred to the Pennsylvanian system. The lowest member, previously known as the Lower Bend shale, is here named the Barnett shale. Many of its fossils are closely related to the Upper Mississippian

forms, while some indicate a possible Pennsylvanian age. From the standpoint of stratigraphic relations the Barnett shale seems to be inseparable from the beds which overlie it. The conclusion of the authors is that the Barnett shale is probably Pennsylvanian, and may be correlated with the lower part of the Morrow group of northern Arkansas and northeastern Oklahoma. The Marble Falls limestone, the middle member of the Bend group, has a fauna similar to that of the Morrow group. It may be correlated also with the Wapanucka limestone of southern Oklahoma. It is certainly older than any of the Pennsylvanian divisions which have been described in the northern Mid-Continent region. The Smithwick shale, the upper member of the Bend group, contains a fauna of which a very important element is confined, as far as is known at present, to this formation. All of the associations of this fauna appear to be with the Pennsylvanian, although the occurrence of such a form as *Bembexia nodomarginata* is an interesting remnant of Mississippian aspect.

A. H. B.

Fauna from the Eocene of Washington. By Charles E. Weaver and Katherine Van Winkle Palmer. University of Washington Publications in Geology, Vol. I, No. 3, pp. 1–56, pls. VIII–XII, June, 1922.

This, the third of the series of geological publications of the University of Washington, is a decided improvement upon the two preceding numbers and appears, on the whole, to be equal to the best of the many papers which have appeared on the West Coast Eocene. The authors describe the University of Washington collecting stations from 315 to 370; describe one new genus, *Phaenomya*, of freshwater Pelecypoda; and describe fifty-six new species and four new subspecies of mollusks. (Not 64 new species as stated on page one.)

Although the paper has fewer errors than many which have appeared of late years on the paleontology of Western Eocene, there are some points open to criticism, the most important of which, it is hoped, the authors will correct in the "Stratigraphical and Faunal History of Northwest Eocene" to be published later. It is not clear why the first two papers of the series had continuous pagination and plate numbers while this one goes back to page one, but does not interrupt the plate series. Six years have elapsed since the appearance of the first number of the series of publications; at this rate therefore an index to Volume I may not be expected for several more years; in the meantime an alphabetical

arrangement of the species would have been much more convenient to the user than the systematic arrangement which was adopted. It is necessary now for each student to prepare his own index or hunt laboriously for any species which he may wish to consult.

The unqualified use of subgenera in place of genera may have some points of advantage, but the plan is open to severe criticism on the ground of the enormous bibliographical difficulties involved; it would seem that whatever system or method is used, an author should at least be consistent in the same paper. The authors here describe *Epitonium* (*Boreoscala*) *washingtonensis*, new species, and figure it as *Epitonium washingtonensis* leaving out the subgenus; but they describe *Pyramidella* (*Syrnola*) *vaderensis*, new species, and figure it as *Syrnola vaderensis*, leaving out the genus; etc.

The authors have failed to designate type specimens of their new species, and do not state where the described and figured specimens are located although such has been accepted museum practice for many years. The original collection was divided into two parts, one of which was taken to Cornell University for study, but the reader is left entirely in the dark as to where the actual specimens described and figured may be consulted. This is a matter of great importance because many of the descriptions contain no comparisons with other species.

The illustrations are from photographs and are much better than any which have previously appeared in this series of the University publications. *Nerita washingtoniana* (Pl. XI, fig. 4.), however, is represented by a mere blotch of light while the description is so generalized that it is entirely unrecognizable.

The authors have tangled the nomenclature of two freshwater gastropods to an unpardonable degree. On page 44, *Goniobasis hannibali*, new species, is described as "extremely variable." The extreme form in sculpture has been taken for the type of the species. *Goniobasis olequahensis* (Arnold and Hannibal) represents the smooth type of shell. . . . . The collection contains specimens which show transition stages between the two types of shell. . . . . One must then wonder why the "new species" was described at all. They state that Dr. H. A. Pilsbry has determined *Ambloxis olequahensis* Arnold and Hannibal to be a *Goniobasis*, yet on the same page (45) they describe *Goniobasis olequahensis* new species! If new, why was not another name chosen?

It is noted that the measurements published in the descriptions are far from being in agreement with the statements given in the explanations of the plates in some cases, as for instance, *Lima packardi* (p. 15).

The continued repetition of certain specific names in different genera, is of course acceptable under the rules of nomenclature, but it is exceedingly troublesome to those who are obliged to use the publications; it often happens that subsequent authors transfer species from one genus to another without cross references and difficulties are multiplied enormously. The specific names, *washingtonensis*, *washingtoniana*, *cowlitzensis*, *olequahensis*, and *vaderensis* have been used over and over again in Washington paleontology, and it is with regret that we notice the present authors have added to this assemblage.

Several typographical errors have been noted but the only one seen which is likely to give trouble is on page 34, where *Turritella washingtoniana* is referred to Plate XI, figures 13, 14, 16. The plate number should read XII.

G. DALLAS HANNA

The Story of the North Star State. By D. E. WILLARD. St. Paul, Minnesota: Webb Publishing Company. Pp. 395, Figs. 156.

This work belongs to a new and increasingly important class of geologic literature, whose avowed purpose is to present scientific facts and principles in such simple language that the intelligent general reader may assimilate them. That the author has succeeded admirably in carrying out his aim is the belief of the present reviewer. The geologic history of Minnesota, particularly that of glacial and post-glacial times, has been made into an interesting story without any loss of scientific accuracy.

A. H. B.

Abrégé de Géographie physique. By EMMANUEL DE MARTONNE. Paris: Librairie Armand Colin, 103 boul. St. Michel, 1922. Pp. ii+356, pls. 8, figs. 100.

As its name implies, this is an abridgment of a larger work by the same author, namely his *Traité de Géographie physique* (1st edition 1909, 3d edition 1920). Designed primarily as a textbook, it is addressed to the general reader as well as to the student. The plan of outline is the same as that of the *Traité* but the method of presentation is in general different. Brevity has been secured by leaving out as far as possible concrete examples illustrating the general laws. Not wishing to treat all the questions summarily, the author has chosen the most important or the simplest, setting them forth in a manner as complete as the limited space permitted.

Each of the four parts (Climate, Hydrography, Relief of the Land, Biogeography) is followed first by a list of references furnishing the teacher with the elements for a more detailed study, then by practical exercises designed to verify in the field the newly acquired principles. An entirely new chapter treats of the relations of human geography with physical geography.

In English speaking countries, the class to which the *Abrégé* will appeal chiefly will undoubtedly be teachers of geography. Combining as it does a clear and precise method of presentation with up-to-date scientific accuracy, it constitutes an excellent introduction to the study of physical geography for anyone who reads French.

A. H. B.